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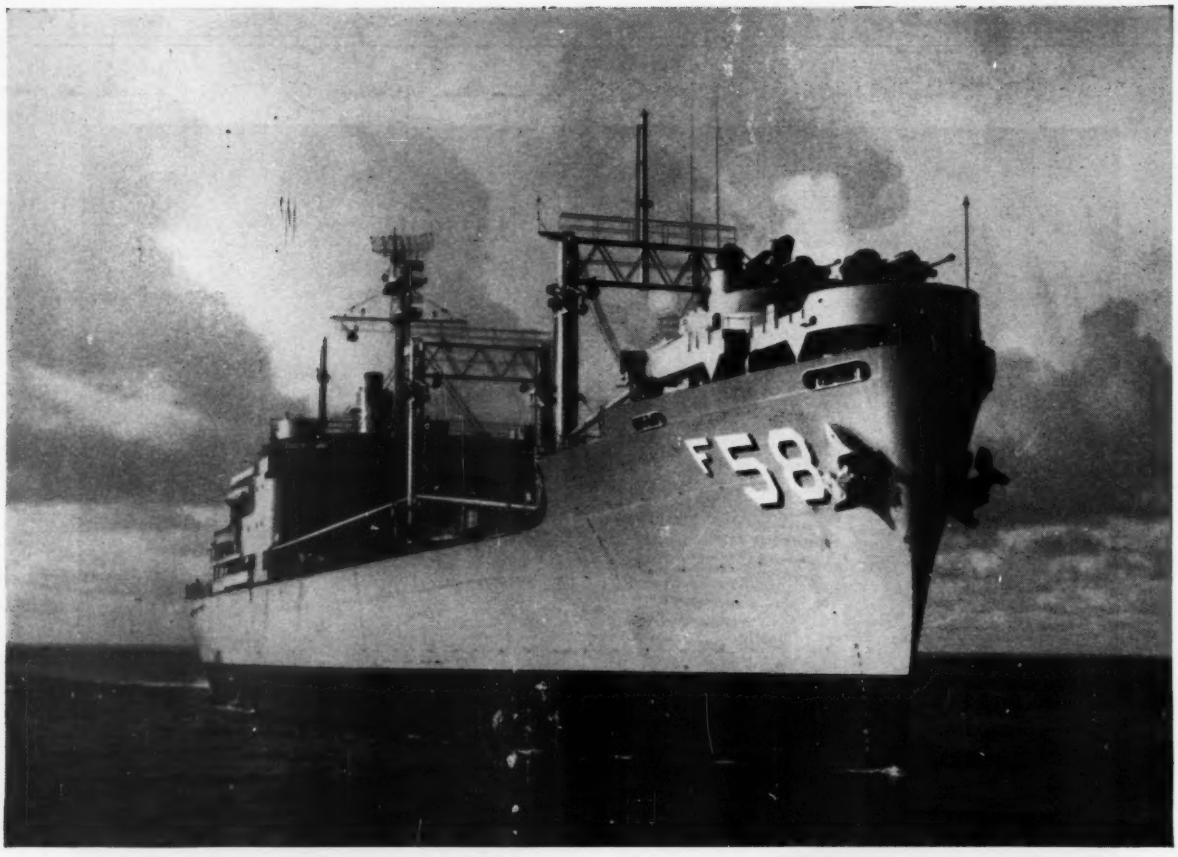

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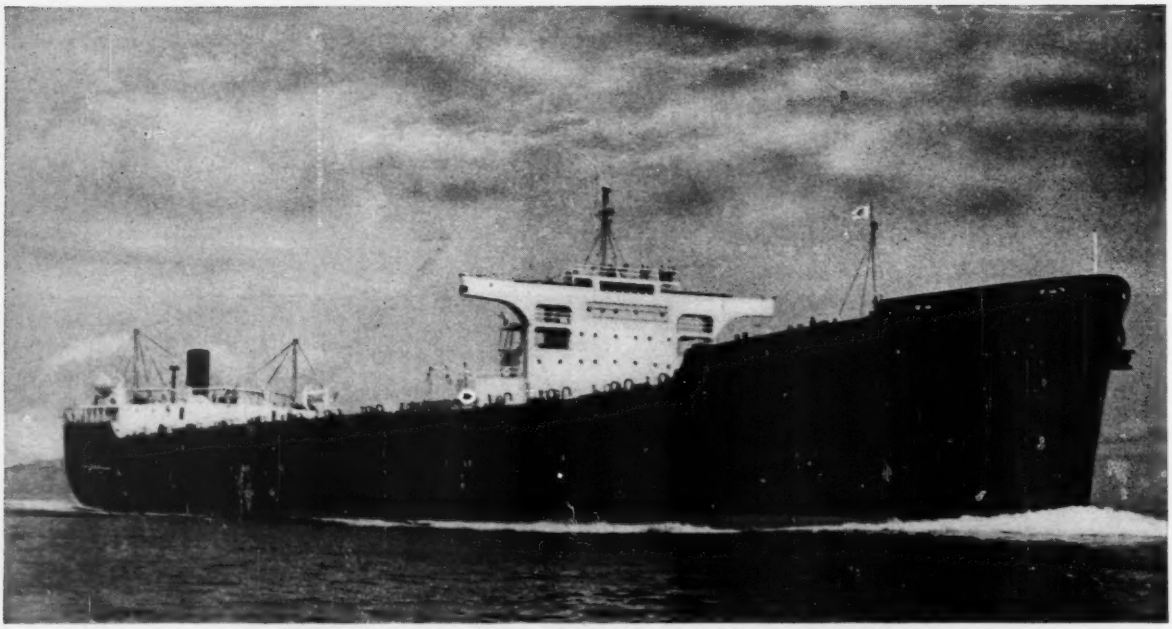

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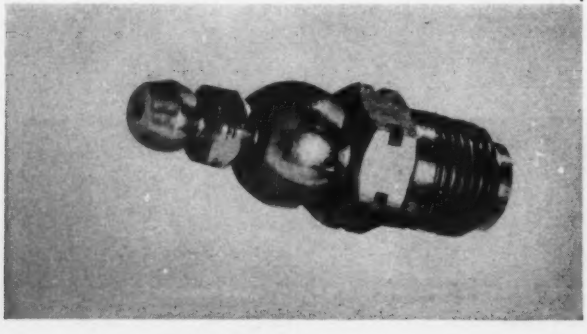

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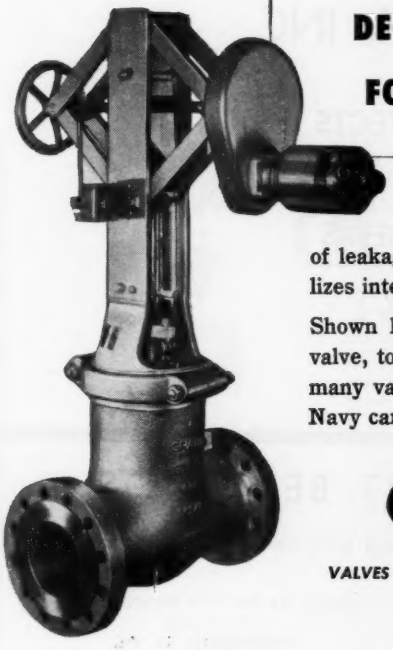

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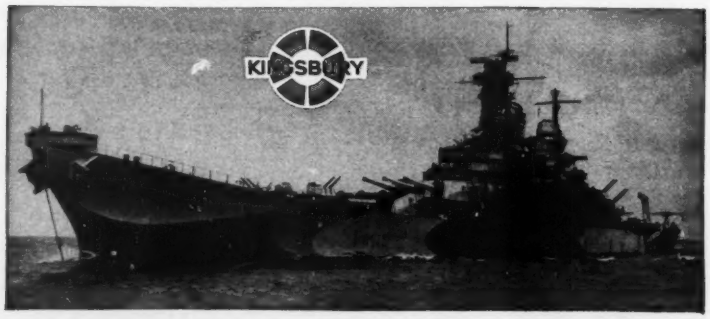

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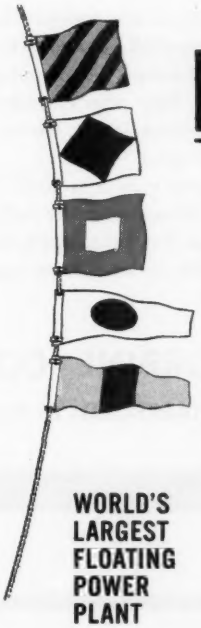

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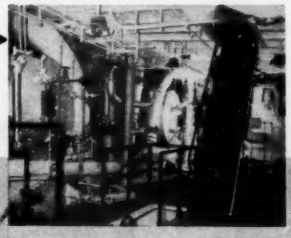

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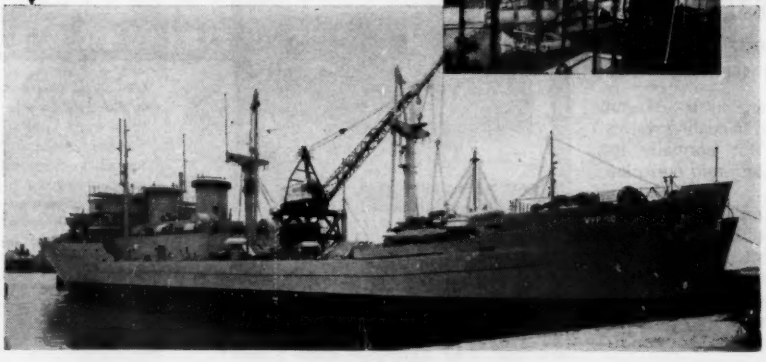

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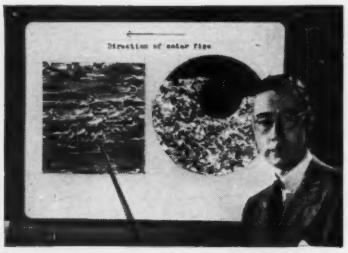

Left, impingement corrosion of Admiralty tube by high velocity sea water with air bubbles. Right, section through part of horseshoe-shaped pit.

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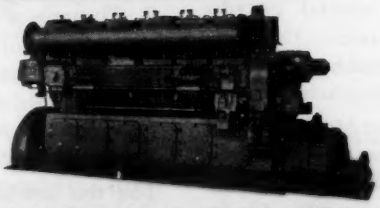
Navy and Coast Guard men who have had experience with C-B Diesels, who have depended upon them in action, know that these fine engines stand for dependability in its broadest sense. Perhaps they do not know that the outstanding performance of every modern Cooper-Bessemer is due in part to a century-old background of engine-building experience. This, combined with



truly advanced engineering, has enabled Cooper-Bessemer Diesels to do a notable job in Navy and Coast Guard vessels from the biggest combat ships to relatively small patrol boats. Yes, you can always count on Cooper-Bessemers for Diesel performance at its finest.

The Cooper-Bessemer Corporation
MOUNT VERNON, OHIO — GROVE CITY, PENNA.

Other "Daily Specials" include tea, cocoa, sugar, rubber, tin, manganese, mahogany, rice, petroleum, silk and even iron ore. These, and many other raw and manufactured products are special because America does not, or cannot, produce them, or produce enough of them. We have to shop for them the world over and we *have* to shop for them in ships.

Here's where the American Merchant Marine should come into the picture. But right now, that picture is a bit out of focus, primarily because ships of other countries are doing the bulk of our shopping for us. As a result, the United States at this moment is in *eleventh* position in merchant ship construction among the world's shipbuilding nations (free and otherwise).

The moral to be drawn is made up of these vital factors:

1. We can depend on foreign flag ships to deliver the goods only so long as they have no prior obligations (anymore than your neighbor is going to pick up your Saturday supermarket order, if he has more pressing things to do).

2. Though we can depend on our phenomenal facility for doing great things in a great hurry, we should not be lulled into a false security. It takes time to build a fast, up-to-date ship of any kind. It takes time to train the men to man it. And the time to take is now.

The ten nations who are ahead of us in merchant ship construction are preparing for nothing but their own safety—safety in their everyday living and safety when their neighbors might say, "Sorry, but we've got problems of our own."

The Babcock & Wilcox Company, which has helped to power so many thousands of American ships, is continuing to work in the tradition of engineering excellence which has made the U. S. A. an acknowledged leader in the design and construction of merchant and naval vessels.

BABCOCK & WILCOX

BOILER DIVISION

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U. S. S. FORRESTAL

ALLIS-CHALMERS
PUMPS

NOW — Ship and Equipment Operating at Sea

ALLIS-CHALMERS — builder of equipment for both Navy and Merchant Marine vessels for nearly sixty years — furnished pumps and electrical equipment for our newest super carrier. Here, where dependability and sturdy construction count most, Allis-Chalmers is a major equipment supplier.

For complete information on Allis-Chalmers pumps and other equipment for ships of all types, call your nearby Allis-Chalmers district office, or write Allis-Chalmers, General Products Division, Milwaukee 1, Wisconsin. A-4858

Equipment for the U.S.S. FORRESTAL furnished by Allis-Chalmers includes:

Fire Pumps
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Catapult Water Brake Pumps
Special Marine Transformers

Builders of propulsion units; pumps, motors, control; condensers and air ejectors; generators, transformers and lighting sets; controllable pitch propellers.

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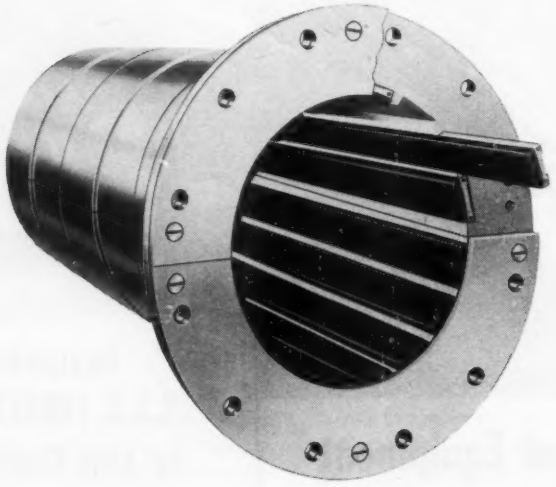
CUTLESS BEARINGS

for

Stern Tubes and Struts



Soft rubber bearing surface—efficiently lubricated by water—this bearing far outlasts all hard surface types, protects propeller shafts, reduces vibration. More than pays for itself in extra wear alone. Saves you time, trouble, and upkeep expense.

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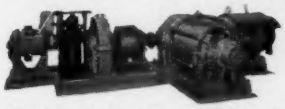
STEAM CONDENSERS...PUMPS
DECK MACHINERY...STEERING GEAR

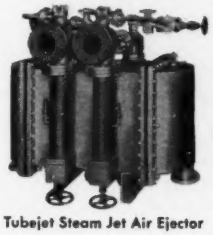
*and half a century of **EXPERIENCE** with all types of marine installations*

Dual Bank Steam Condenser



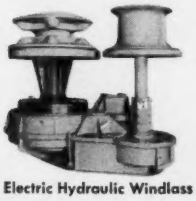
Automatic Tensioning Hoist — Airplane Crane

Electric Hydraulic Deck Winch



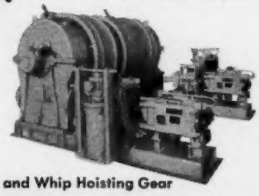
Tubejet Steam Jet Air Ejector

Electric Warping Capstan

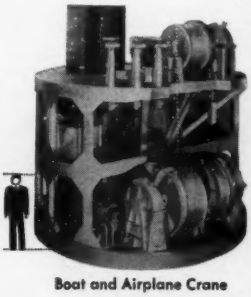


Electric Hydraulic Windlass

Warping Winch



Boat Crane and Whip Hoisting Gear



Boat and Airplane Crane

Steering Gears

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Marine Condensers & Ejectors • Marine Pumps • Deck Machinery • Steam Condensers • Centrifugal, Axial & Mixed Flow Pumps • Steam Jet Ejectors • Vacuum Refrigeration • High Vacuum Process Equipment

DE LAVAL

main propulsion units power the new United States Navy destroyer escorts

Here is the U.S.S. Cromwell, a Navy destroyer escort vessel driven by De Laval turbines through De Laval reduction gears. Also on board are dependable De Laval main boiler feed pumps and IMO pumps. De Laval is supplying the same equipment on twelve sister ships of the DE-1014.

DE LAVAL *Marine Division*

DE LAVAL STEAM TURBINE COMPANY

Trenton 2, New Jersey

DL 315

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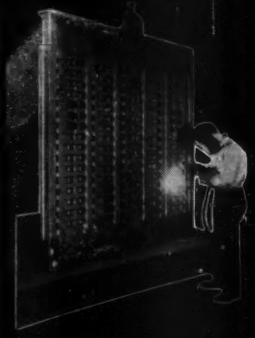


WELDING SOLVES ANOTHER WEIGHT PROBLEM

(and USS "T-1" Steel solves the welding problem!)

Bedplates for modern color-printing presses have to be rugged—but as lightweight as possible. They must withstand constant pounding from printing rollers and cutting knives. And, since they move back and forth continually, they've got to be lightweight for fast, efficient operation. It is a good place to use a welded assembly of steel plate.

But that's where Graver Tank & Manufacturing Co., Inc., ran head-on into a tough fabrication problem. Alloy steel with the necessary strength and durability was difficult to weld. And with 534 welds to make on *every* bedplate, this was a king-size headache.

NO MORE HEADACHE!

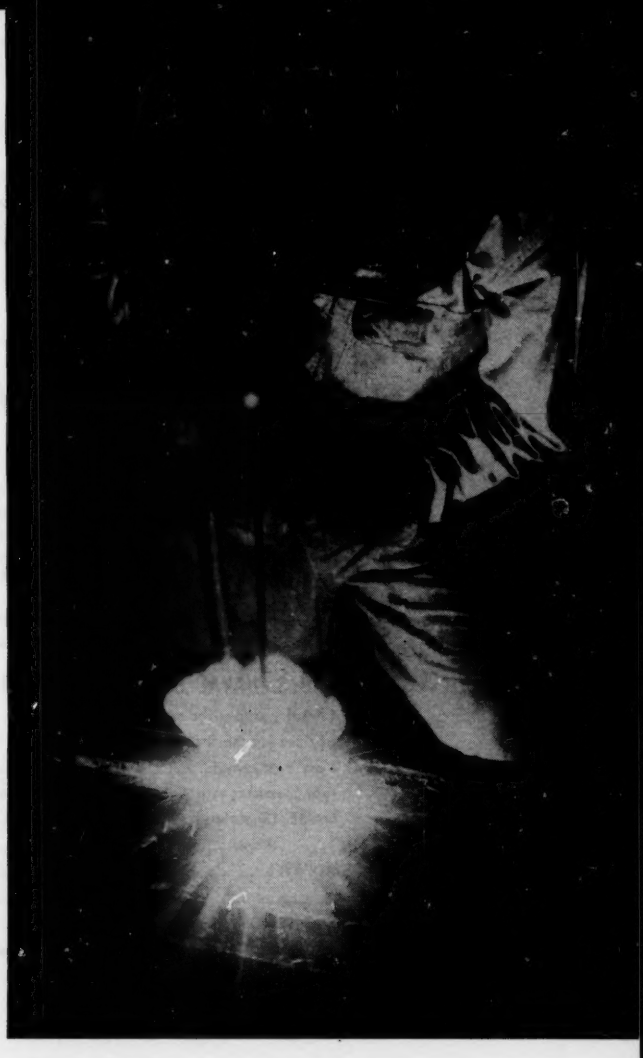
Now the headache is gone. Production costs are down. And the finished bedplates are working hard and long . . . taking a tremendous daily pounding without distortion.

The solution? Just a switch to a remarkable *new* alloy steel, USS "T-1" Steel.

"'T-1' Steel is very strong. Very tough. Able to take vicious impact abuse. Yet, it's easy to weld," says Mr. H. McDonald, Superintendent at Graver.

HOW ABOUT YOU?

If you have tough jobs, rugged jobs, where you want to weld your way to lower costs, give this new steel a try. We think you, like Mr. McDonald, will find it the best thing you have ever used. Right now, "T-1" is in service and doing well in bridges, power shovels, steam turbines, electrical transformer tanks, flywheels, pressure vessels, mine cars, and lots of other places. Write for details. United States Steel, Room 5084, Pittsburgh 30, Pa.



"TOP QUALITY" That's how Graver Tank & Manufacturing Co., Inc., East Chicago, Indiana, describes new USS "T-1" Steel. It gives them a yield strength of 90,000 psi . . . exceptional resistance to impact abuse . . . and good weldability. It enables them to build extremely rugged, all-welded bedplates for printing presses.

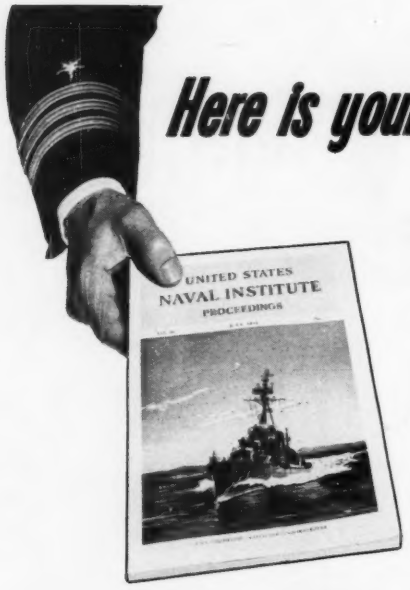
UNITED STATES STEEL CORPORATION, PITTSBURGH • COLUMBIA-GENEVA STEEL DIVISION, SAN FRANCISCO
TENNESSEE COAL & IRON DIVISION, FAIRFIELD, ALA. • UNITED STATES STEEL SUPPLY DIVISION, WAREHOUSE DISTRIBUTORS, COAST-TO-COAST
UNITED STATES STEEL EXPORT COMPANY, NEW YORK

USS "T1" CONSTRUCTIONAL ALLOY STEEL

USS

6-15

UNITED STATES STEEL



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United States Naval Institute Proceedings

for pleasure and profit. The issues contain anecdotes and reminiscences, incidents from history and essays on Navy topics, technical articles and treatises on Naval developments and progress, book reviews and discussions, and international and professional notes. Membership dues (including PROCEEDINGS), $3.00 a year. Subscription rate, $5.00 a year. (Foreign postage, $1.00 extra.) Single copies 50 cents (except some scarce issues).

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U. S. NAVAL INSTITUTE - Annapolis, Maryland Date_____

I hereby apply for membership in the U. S. Naval Institute and enclose $3.00* in payment of dues for the first year, the PROCEEDINGS to begin with the_____issue.

I am a citizen of_____and understand that members are liable for dues until the date of receipt of their written resignations.

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PROFESSION:_____

** $4.00 if residing outside of U. S., its possessions or territories.*

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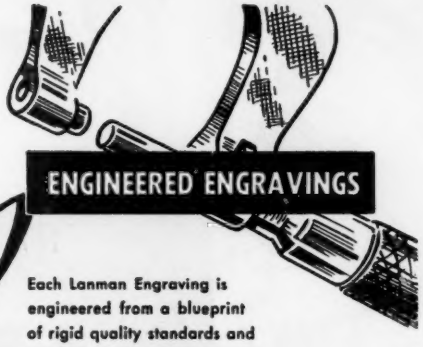
OLDEST
COMMERCIAL
PHOTO-ENGRAVING
HOUSE



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Each Lanman Engraving is engineered from a blueprint of rigid quality standards and precision workmanship . . . for quality and service it's Lanman!

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For 64 years, Cutler-Hammer, Pioneer Electrical Manufacturer, has furnished dependable control to all departments of the United States government. Built to specifications . . . backed by an outstanding record of performance.

CONTROL APPARATUS FOR ALL MARINE USES

Motor Control for Every Service, Ventilating Fans, Pumps, Cargo Winches, Capstans, Windlasses, Laundry Machines, etc.

Magnetic Brakes	Rheostats
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Limit Switches	Magnetic Clutches
Solenoids	Pushbuttons

CUTLER-HAMMER, Inc., 1354 St. Paul Avenue, MILWAUKEE 1, WIS.

CUTLER-HAMMER
MOTOR CONTROL
C-H

Looking for a TOUGHER STEEL?

Unusually tough, even at sub-zero temperatures, Lukens "T-1" steel can reduce equipment costs.

Failure from abrasion or from impact can happen to the steel in your equipment, too. Here's the answer — the tougher steel you've been looking for. Lukens "T-1" steel has excellent resistance to the combination of wear and impact, is tough enough to withstand unusual stresses and pressures as well as shock at either sub-zero or high temperatures, thus lowering maintenance costs and lengthening equipment life.

Because of its high yield strength (over 90,000 psi) this new, all-purpose steel offers lighter weight and reduced thickness in comparison to heavier, thicker plates of carbon steel, thereby reducing material, construction and shipping costs. Engineers and designers can take advantage of Lukens "T-1" steel's many superior properties, such as its ready weldability and excellent wear characteristics, which will pay off in design freedom and increased equipment efficiency. And Lukens' range of steel plate sizes—including the widest and heaviest plates available anywhere — makes possible additional savings through the use of wider plates that require fewer welded seams.

The latest addition to Lukens' complete line of carbon, alloy and clad steels, this quenched and tempered alloy plate steel's unusual combination of properties suit it especially to application in pressure vessels, bridges, shipbuilding, construction machinery and general industrial equipment. On problems of design, selection, application and fabricating techniques, Lukens offers full technical assistance. If you would like further information on Lukens "T-1" steel, write for the new 28-page Bulletin 781. Address: Manager, Marketing Service, 821 Lukens Building, Lukens Steel Company, Coatesville, Pa.

LUKENS

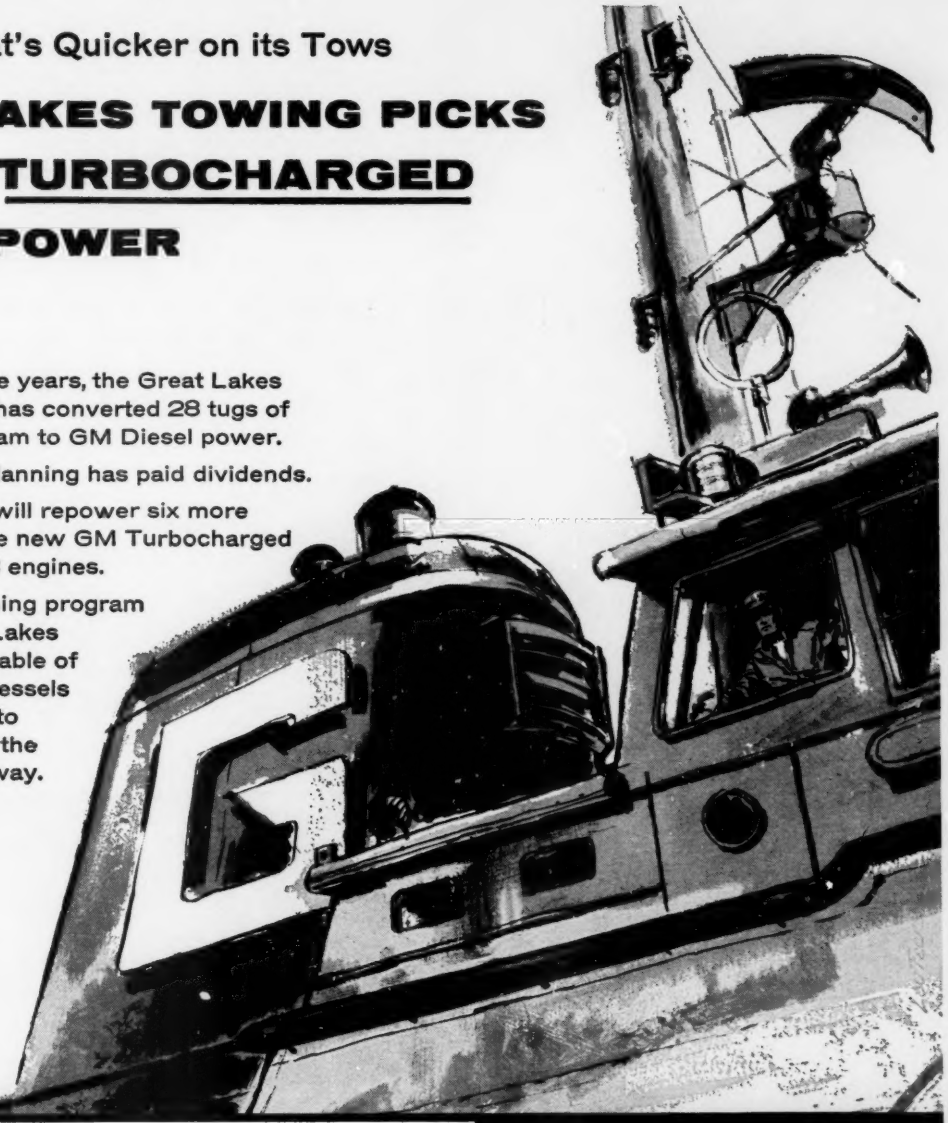
"T-1" STEEL

THE NEWEST IN A COMPLETE LINE OF ALLOY STEELS

LUKENS STEEL COMPANY, COATESVILLE, PENNSYLVANIA

For a Tug that's Quicker on its Tows

GREAT LAKES TOWING PICKS GM TURBOCHARGED DIESEL POWER



Within the past five years, the Great Lakes Towing Company has converted 28 tugs of their fleet from steam to GM Diesel power.

This progressive planning has paid dividends.

Now Great Lakes will repower six more steam tugs with the new GM Turbocharged 2-cycle Model 498 engines.

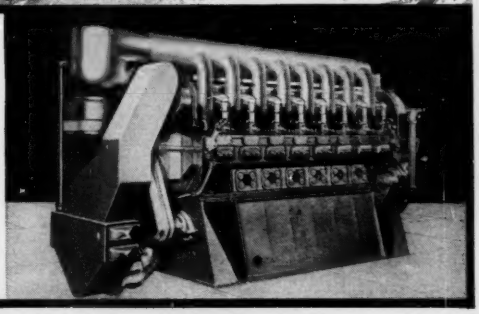
This forward planning program means that Great Lakes Towing will be capable of handling all large vessels which will come into the Lakes through the St. Lawrence Seaway.

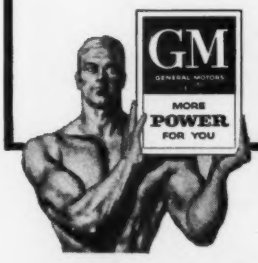
The New Series 498

GM TURBOCHARGED DIESEL

gives you

75% more power per cylinder
60% more power per cubic foot
60% more power per pound
12% lower specific fuel consumption
36% minimum thermal efficiency





CLEVELAND DIESEL

Engine Division of General Motors, Cleveland 11, Ohio

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San Francisco, Calif., 870 Harrison St. Tel.: Douglas 2-1931
Seattle, Wash., 1230 Westlake Ave. N. Tel.: Adler 1440
Wilmington, Calif., 433 Marine Avenue. Tel.: Terminal 4-4098

"For Want of a Nail..."

For want of a nail the shoe is lost,
for want of a shoe the horse is lost,
for want of a horse the rider is lost.

George Herbert's statement applies to electronics today as it did to riders three centuries ago. The point may be illustrated by considering a vital electronic unit made up of thousands of components. If the least of these components fails, the whole unit may fail—and with it a strategic military mission.

The problem of *reliability* is becoming increasingly important as the science of electronics advances. "Black boxes" are hard pressed to perform more complicated tasks with increasing efficiency. And at the same time, the requirements call for smaller dimensions. Notwithstanding environmental extremes of an order hitherto unknown, every resistor, capacitor and relay *must* perform *reliably*. Each "nail" is critical.

That is why RCA is continuing its vigorous search for ways and means to increase the reliability of every component in an electronic unit. This program never ceases. It follows through from design to field evaluation. Everything learned is immediately applied to current development and production.

In seeking a degree of electronic perfection never before attained, RCA joins hands with others in this field. This matter of *reliability* is an industry challenge to be met by ingenuity, brain power and engineering knowledge wherever it is found.

DEFENSE ELECTRONIC PRODUCTS
RADIO CORPORATION of AMERICA
CAMDEN, N.J.

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Journal of the AMERICAN SOCIETY of NAVAL ENGINEERS, Inc.

VOLUME 68 FEBRUARY 1956 NUMBER 1

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COUNCIL OF THE SOCIETY

(Under whose supervision this number is published)

Rear Admiral K. K. COWART, USCG, President

Rear Admiral RAWSON BENNETT, USN
Captain PETER V. COLMAR, USCG
Rear Admiral R. E. CRONIN, USN
Rear Admiral L. V. HONSINGER, USN
Captain PETER HORN, USN
Commander E. G. KINTNER, USNR
Mr. JAMES S. MELTON
Lieutenant Commander J. W. SAWYER, USNR
Mr. THOMAS B. SHEPARD, JR.

Captain J. E. HAMILTON, USN (Ret.), Secretary-Treasurer

SECRETARY'S NOTES

Election for 1956:

The following report was submitted by the ballot counting committee to the meeting of the Joint 1955-1956 Council on 4 January 1956.

4 January, 1956

"Captain J. E. Hamilton, USN (Ret.)
American Society of Naval Engineers, Inc.
Washington, D.C.

MY DEAR CAPTAIN HAMILTON:

In accordance with your letter of November 22, 1955, the Committee appointed thereby, consisting of the undersigned as Chairman, Mr. David McAulay, Mr. John D. Crosby, and Mr. Leverett A. Meadows, to count ballots cast for officers of the Society for the ensuing period, on proposed Honorary Memberships, and on the proposed amendment to the By-Laws, submits the following report:

Total Ballots cast 1329

For President	Rear Admiral K. K. Cowart, USCG	1264
For Secretary-Treasurer	Captain J. E. Hamilton, USN, Ret.	1081
	Captain W. R. Millis, USN, Ret.	231
For Member of Council	Captain W. I. Bull, USN	410
	Captain J. M. Farrin, USN	592
	Rear Admiral L. V. Honsinger, USN	902
	Captain Peter Horn, USN	654
	Commander C. H. Campbell, USNR	638
	Commander E. G. Kintner, USNR	640
	Captain Richard D. Schmidtman, USCG	589

Rear Admiral KENNETH K. COWART, U. S. Coast Guard; Engineer-in-Chief

President of The Society for 1956

JOINT MEETING OF THE 1955 AND 1956 COUNCILS — 4 JANUARY 1956

Seated: Captain Peter V. Colmar, USCG, Council 1956-7; Commander E. G. Kintner, USNR, Council 1956-7; Captain Peter Horn, USN, Council 1956-7; Rear Admiral Kenneth K. Cowart, USCG, President 1956; Rear Admiral F. R. Furth, USN, President 1955; Rear Admiral L. V. Honsinger, USN, Council 1956-7; Mr. Thomas B. Shepard, Jr., Council 1956-7; Mr. A. G. Fessenden, Administrative Assistant 1908-. Standing: Mr. Mark Swanson, Chairman Ballot Committee; Captain R. B. Madden, USN, Assistant Secretary-Treasurer; Rear Admiral Rawson Bennett, USN, Council 1955-6; Captain C. H. Campbell, USN, Council 1954-5; Commander J. W. Naab, USCG, Council 1954-5; Mr. John Hanlon, Council 1954-5; Rear Admiral R. E. Cronin, USN, Council 1955-6; Captain J. E. Hamilton, USN (Ret.), Secretary-Treasurer. Absent: Captain W. D. Brinckloe, USN, Council 1955; Captain J. M. Farrin, USN, Council 1955; Mr. James S. Melton, Council 1955-6; Lieutenant Commander J. W. Sawyer, USNR, Council 1955-6.

Captain Peter V. Colmar..... 661
USCG
Mr. Thomas B. Shepard, Jr..... 697
General Electric Co.
Mr. F. J. Lindauer..... 600
Fairbanks Morse & Co.

Proposed for Honorary Membership		For	Against	No Vote
	Mr. K. D. Williams	1075	38	
	*Mr. E. C. Magdeburger	1069	45	115
	Mr. Arthur G. Fessenden	1157	22	
Proposed Amendment to By-Laws		1169	106	54

*Deceased after ballot distributed.

Sincerely,

Copy to:
Mr. David McAulay
Mr. John D. Crosby
Mr. Leverett A. Meadows

MARK SWANSON, *Chairman.*"

As a result the Council announces that the President for 1956 will be Rear Admiral Kenneth K. Cowart, USCG. Admiral Cowart's photograph appears on page two of this issue. The Secretary-Treasurer, having been reelected, will continue in office. Captain R. B. Madden, USN and Mr. Arthur G. Fessenden were continued as Assistant Secretary-Treasurer and Administrative Assistant, respectively, by action of the Council.

The complete list of the 1956 Council will be found on page 1. The election resulted in the following changes:

Rear Admiral L. V. Honsinger, USN, succeeds Captain J. M. Farrin, USN.

Captain Peter Horn, USN, succeeds Commander W. D. Brinckloe, USN.

Commander E. G. Kintner, USNR, succeeds Captain C. H. Campbell, USNR.

Captain Peter V. Colmar, USCG, succeeds Commander J. W. Naab, USCG, and

Mr. Thomas B. Shepard, Jr., succeeds Mr. John F. Hanlon.

The term of the new members extends to 1 January 1958.

Rear Admiral Frederick R. Furth, USN

Admiral Furth who retired as President of the Society on 31 December 1955, also retired from active naval duty. He has joined International Telephone and Telegraph Corporation as assistant to the president of Farnsworth Electronics Company division at Fort Wayne, Indiana.

Navy Recruiting
Bureau of Ships, etc.

The Navy's mission to control the seas is old but very valid and desperately serious. This cannot be done without sufficient man-power.

New and greater emphasis is now being placed on naval personnel programs, in order to maintain an acceptable degree of combat readiness and to meet the Navy's world-wide commitments. Spearheading this drive for recruits and reenlistees is an Ad Hoc Committee established by the Chief of Naval Personnel, Vice Admiral James L. Holloway, Jr.

The function of this committee is to coordinate the efforts of those whose energies are being directed toward the successful completion of its task. But the success of it depends upon more than one group. The combined efforts of all the Navy's friends are required, if the unprecedented recruiting requirements are to be met. This is where members of the Society come into the picture.

By our understanding of the problem, and our knowledge and appreciation of career opportunities and advantages of naval service, we are in a position to help.

The Secretary of the Navy has asked us to provide such assistance as is practicable to this recruitment and reenlistment campaign.

Bureau of Ships Functional
Engineering Practices Project

Recently the Bureau of Ships initiated a project to undertake studies for the improvement and simplification of ships drawings, reproduction methods and associated drawing communications between shipyards. The goal of this project is the generation, testing and promulgation of methods for saving time and money in the processing of normal naval design work.

This project has been undertaken because, now, as never before, there is an urgent demand for increasing the personal effectiveness of technical personnel, because of their acute scarcity and also out of economic and military necessity.

Because of the extremely broad technical spread of ship components it is felt that this project will be of special interest to the entire engineering profession. Therefore, the Bureau has approached the engineering societies for aid in developing information to be used in this program.

Specifically, the Bureau of Ships requests that anyone knowing the names of organizations or people in the technical fields who have developed papers, systems or techniques covering simplified or functional drafting, communicate with the San Francisco Naval Shipyard, attention: Design Division, Code 242P, San Francisco 24, California.

Rear Admiral Rawson Bennett, USN

Upon the retirement from active Naval duty of Rear Admiral Furth, Captain Bennett who is a member of the Society's Council was appointed to relieve him as Chief of Naval Research with the rank of Rear Admiral.

Armed Forces Day—May 19, 1956

The following release has been received from the Department of Defense:

"I call upon my fellow citizens not only to display the flag of the United States on Armed Forces Day, thus manifesting their recognition of the sacrifices and devotion to duty of the Armed Forces, but also to avail themselves of this opportunity to further their knowledge of our defense system and of the men and women who constitute its real strength, by attending and participating in the local observances of the day, conducted by the Armed Forces and the civil authorities."

—From the 1955 Armed Forces Day Proclamation of President Dwight D. Eisenhower

Background. Prior to 1950, Army Day was celebrated on April 6 each year, Air Force Day on September 18, Navy Day on October 27, and the Marine Corps Anniverstary on November 10. In April 1949, the Secretary of Defense with the President's approval announced that the four separate events would be consolidated into a single annual observance of ARMED FORCES DAY. The designation of a single occasion was in line with the unification of the Services and the creation of the Department of Defense by act of Congress. Thus, Armed Forces Day was intended to symbolize unification, demonstrate the close working relationship of the Army, Navy, Air Force, Marine Corps, Coast Guard and the Reserve Components, and give the public an annual report on the state of the Nation's defense forces.

Date. In selecting a date for this annual observance, the Department of Defense gave lengthy consideration to weather and other important factors. It was generally agreed that such an observance could not be held in the winter months because of the weather, nor in the summer because schools and colleges would be unable to participate, and that any date in the fall would conflict with school and college sports events. It was also agreed that the date must not be too near any established national holiday, such as Independence Day or Veterans Day (formerly Armistice Day). By process of elimination it was finally concluded that the third Saturday in May would involve the least conflict with established public events and the least interference with business, industry, education, and other elements of national community life, and would therefore be most likely to achieve the greatest public participation nationwide. Accordingly, the President proclaimed the Third Saturday in May, 1950, as the first Armed Forces Day.

Slogan. From the first, the Armed Forces Day observance has been devoted to emphasis upon the basic concept that our national security and our free way of life depend upon the power which comes from American teamwork and national unity. The 1950 slogan was TEAMED FOR DEFENSE. The 1951 program featured DEFENDERS OF FREEDOM. The 1952 banner was UNITY—STRENGTH—FREEDOM. The 1953 observance was keyed to the fact that the Armed Forces of the United States represent POWER FOR PEACE—a slogan so appropriate to our national intentions that it was retained for the 1954 and 1955 programs and will be used again for the 1956 Armed Forces Day observance.

Type of Observance. Although Armed Forces Day is a public event and has been the occasion for a wide variety of community activities, the observance is now essentially an "open house" program designed to promote public interest in and understanding of the Armed Forces of the United States. Wherever feasible, the public is invited to visit posts, camps, stations, bases, armories, reserve centers, and other facilities in our national defense system. The public is, in effect, given an opportunity to make an annual inspection of that system, in which every American has a stake.

Participation. Although major emphasis of Armed Forces Day is on the primary components of the defense team—Army, Navy, Air Force, Marine Corps, Coast Guard, and Reserve Components—invitations to participate have also been extended in the past to organizations and programs supporting the defense effort. These include U. S. Savings Bonds, National Blood Program, Civil Defense, Red Cross, United Services Organization, Ground Observer Corps, Civil Air Patrol, and Selective Service.

Public Interest. Records show that the public has taken advantage of the opportunity to see their defense team in operation. In 1953, more than 500 "open house" programs at Armed Forces installations in the United States and overseas were attended by more than four million men, women and children. In 1954, more than 2,300 such "open house" programs at posts, camps, stations, bases, ships in port, armories, reserve centers, Ground Observer Corps, Civil Air Patrol, and other defense facilities, attracted more than seven million visitors. In 1953 it was estimated that at least five million people viewed 433 Armed Forces Day parades and that one and a half million participated in armory and reserve center programs or attended displays, demonstrations, luncheons or other activities in approximately 1,300 communities. In 1954, nearly eight million people witnessed the 562 parades and reviews in which approximately half a million uniformed personnel participated, and more than two and a half million attended or participated in 1,681 community events.

In 1955, more than 2,500 "open house" programs at posts, camps, stations, bases, ships in port, armories, reserve centers, GOC filter centers, CAP airports, and other related facilities reported attendance of more than 7,500,000 men, women, and children. Parades and reviews in which approximately half a million uniformed personnel participated were witnessed by more than 9,000,000 people. More than 2,000 community programs, such as luncheons, dinners, rallies, displays, demonstrations and other sponsored activities drew an estimated 3,000,000 people. In 1955, the Armed Forces Day program had a direct impact upon nearly 20,000,000 people in the United States and abroad.

1956 Program. Information as to national, state or local plans for the observance of Armed Forces Day on May 19, 1956, may be obtained at any Armed Forces command or from the Office of Public Information, Department of Defense, Room 2E788, The Pentagon, Washington 25, D. C.

Article by Commander Knox:

The following letter has been received from the Commander of one of the Naval Shipyards:

"I have been very much impressed with the article in your November 1955 issue on 'How to Improve Your Shipyard Overhaul,' by Commander Robert J. Knox. The article is being reproduced in accordance with the JOURNAL's conditions for reprinting and will be made a permanent part of our booklet, 'Information to Ships.' It is believed that it will prove most helpful in enabling this Shipyard to do a better job for our customers."

Science Education

Members of the Society are certainly aware of the shortage of scientists and engineers in the United States. Most of them are probably equally aware of the efforts which are being made to improve the situation.

Although the Council feels that it has no authority to participate in local affairs in behalf of the Society it has decided that it can and should lend moral support to those activities which are designed to counter the shortage of technically educated personnel. As concrete evidence of this support, the Council has donated $100.00 of Society funds to be used for promoting the Science Fairs which are to be held in the Washington area and the Joint Board on Science Education of the Washington Academy of Science and

the District of Columbia Council of Engineering and Architectural Societies.

Geneva Conference on Atomic Energy:

In this issue are two articles which stem from the recent conference on Atomic Energy which was held in Geneva. A reprinted article by Mr. G. W. K. Ford, taken from "Engineering" starts on page 22. An original article by Robert W. Clack, a member of the Society will be found on page 45. Although there appears to be a difference in views on the economies of Power Reactors for commercial power generation this may represent a difference between basic economies of two countries or merely one view which is more conservative than the other.

In keeping with the Society's traditions, we hope to devote considerable space in the JOURNAL to all aspects of this latest form of power generation.

Format of the Journal

The Council and Editor are awaiting the reactions of readers to the new Format which appears for the first time in this issue. Any comments will be very gratefully received. We will particularly welcome suggestions for improvement.

This February issue is a trial run. It does not represent "standards" which have been adopted for all future issues. For most articles we have gone to a larger type size in the interest of improved readability.

This issue is somewhat larger than can be expected in the future. At present rates we could not afford to maintain the JOURNAL at this size for four issues a year. This has been done for the inaugural issue in order to practice layouts of as many types of articles as were available.

We believe that the conversion to the new format has been well done. If that is so much of the credit is due to our printer, The Benson Printing Co. of Nashville, Tenn. and to our engraver, The Lanman Engraving Co. of Washington, D.C. They have met every demand placed upon them and have contributed very heavily with sophisticated suggestions throughout the entire task. Our advertisers are also to be thanked for their cooperation.

This, in no manner is intended to pass the buck for faults. For any of these, large or small, the Editor, backed by the Council takes full responsibility.

The USS BOSTON (CAG-1) is the Navy's first guided missile cruiser capable of firing supersonic anti-aircraft guided missiles. It represents a completely new concept in a naval weapon system.

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The second of ten FORREST SHERMAN-class destroyers, USS JOHN PAUL JONES (DD 932), has been launched. The 418-foot vessel mounts the Navy's latest developments in electronics, gunnery, nagivational, engineering and anti-submarine equipment, as well as the newest comfort features for her 350-man crew.

HAROLD J. BOWEN
Captain, MC, U. S. Navy

LOGISTICS, NAVY STYLE

THE AUTHOR

is from Charleston, South Carolina. He was educated at Georgia Tech, the University of North Carolina and the Medical College of South Carolina, with post graduate training in plastic surgery at the Mayo Clinic. In World War II he was Senior Medical Officer of a cruiser in the Pacific and Surgeon at the U.S. Naval Hospital, Aiae, Hawaii. Following his graduation from the U.S. Naval War College in 1948, he was assigned to the faculty of the Armed Forces Staff College in the Research and Development, and Logistics Departments, where he served from 1948 to 1950. He was ordered to Europe in 1950 as Senior Staff Medical Officer for the Commander, U.S. Naval Forces Eastern Atlantic and Mediterranean, where he served under Admirals R. L. Conolly, R. B. Carney and Jerauld Wright, for thirty (30) months. During this period he was engaged in logistics planning for the Commander, U.S. Naval Forces Eastern Atlantic and Mediterranean; the Commander, Allied Forces, Southern Europe; and the Commander, Naval Forces, Southern Europe. His present assignment is Senior Medical Officer, U.S. Naval Training Center, Great Lakes, Illinois.

MOST COMPETENT MILITARY AUTHORITIES agree that it is unlikely that precise and uniformly adaptable formulae for the successful conduct of warfare will ever be evolved. It is, however, generally agreed that there exists an ever increasing necessity for the civilian heads of our National Defense Establishment, as well as our Military Commanders, to acquire a clear, comprehensive, and almost instinctive understanding of the fundamental nature of warfare, and of the dynamic and philosophical relationships that exist between those basic elements which enter into its complex make-up. Despite the great need for such understanding, it is most painful to relate that a consummate appreciation of the immediate force of impact which these elemental relationships exert upon our National war potential, and their more remote effect upon our ability to survive as a Nation, is all too rare in the Line, rarer in the Staff Corps, and found only occasionally among the majority of appointed civilian leaders.

Yet, in spite of all of the attendant difficulties of mastering a workable understanding of these relationships, both the civilian and the military authorities who bear the responsibility for our National security and survival must, perforce, somehow acquire a more penetrating comprehension of the military, political, and economical implications of these inter-related factors. Further, they must also be able to collimate them into some sort of rational pattern, in order to get on with the serious business of planning and preparing for war. To accomplish such objectives all those individuals concerned must earnestly dedicate themselves to the study of the broad spectrum of history, philosophy and economics; but above all, they must be taught to think in strategic military, as well as in politico-economic terms in order to be able to translate, with reasonable accuracy, a shapeless and often incoherent mass of military postulates, strategic global concepts, and logistical desiderata, into a variety of sharpened military weapons ready in our hands for instant use should war occur.

Now it has been observed, particularly by military teachers, that even the most casual student of warfare soon becomes aware of the intimacy as well as the intangibility of the natural relationships which exist between strategy, tactics, and logistics. Also, and in spite of the efforts of the scholar and tyro alike, to establish clear-cut boundaries between them, these relationships still remain among those military imponderables which defy exact analysis or rigid classification.

To gain a really lucid and comprehensive perspective of the Navy's logistical philosophy it should be thoroughly understood at the outset that the Navy believes that logistics, like those other functional staff divisions such as personnel, intelligence, and operations, is not only sired by strategy, but is also one of its engenerate components. Further, it is the Navy's thorough conviction that, though strategy is undoubtedly the prime schematic motivating factor in Naval operations, logistics is the actual implementing force thereof.

The Navy also acknowledges the tenet that all military logistics must be governed and regulated by certain intrinsic and unalterable national economic factors; and, finally, that the attainment of internanational strategic military, political and economic objectives is the principal reason for the continued existence of our great and highly complex Naval establishment. With this triphasic thesis in mind, it becomes a consensual fact that strategy must at times defer to civil economic, as well as military logistical, considerations.

With this somewhat eclectic background we can now proceed. Although it seems entirely accurate to state that naval logistics derives its original generic form from that course of action which is strategically desirable, it is equally true that logistic factors and considerations, per se, often determine what courses of action may actually be strategically possible. For, like any truly indispensable servant, logistics frequently becomes the master. It is believed that this general thesis is now accepted by most really experienced commanders.

At this point it would seem appropriate to provide the reader with a practical Navy definition of logistics. However, in attempting to define Naval logistics, it is well to remember that it is really not too important for one to have the exact semantic nuances of these two words for, after all, they are but articulate sounds and not realities. Realities are truths, and truth remains the same regardless of its definitions, terms, or symbols.

An official definition of logistics can be found in the Dictionary of U. S. Military terms, a Joint Chiefs of Staff publication. However, since this booklet fails to specifically define naval logistics, I shall abridge formal semantics and do this for you by synthesizing the usually accepted meanings of the words naval, and logistics.

By this syntactical maneuver, we find naval logistics to be that branch of the naval art or science which embraces all of the details, techniques, and procedures, of providing all of the means for the conduct of naval operations. Thorp, in a miniature classic, "Pure Logistics," says this with even more cogency: "Strategy and tactics provide the scheme for the conduct of military operations, logistics provides the means therefor."

According to the poet, Walter Savage Landor, "We are what the suns and winds and waters make us"; therefore, to fully grasp the Navy's concept of logistics and assign it to its rightful niche within the broad framework of naval thought, one must first know and appreciate the sequential influences as well as the chronological professional development and logistical education of the "standard" Naval line officer. To many Naval officers of yesteryear, logistics simply meant the process of supplying the ships and fleets with the beans, bullets, and bunker oil, needed to keep them operating and/or fighting. Today that naive concept is undergoing drastic, and in some instances, revolutionary changes.

Today's neophyte Naval officer, starting his career as a junior watch and/or division officer, soon begins to fathom and identify the requisitioning techniques and the various distribution channels through which the weapons and equipment he is learning to employ are procured, maintained, and when necessary, replaced.

This knowledge and training, along with a wider appreciation of his military responsibilities, is further augmented as he moves up in rank and responsibilities to senior watch or division officer, and shipboard department head; but by the time he has risen to command, the scope of his experience has usually been greatly expanded. Of course, the larger the vessel or station and the more complex its mission, the wider will be the range of his duties and responsibilities. However, irrespective of the size, type, or mission of the ship or station, it is a commanding officer's inescapable obligation to thoroughly master all procedures relating to its technical operation and maintenance, all of the military missions likely to be required of ships or installations of that type, and all of the factors affecting the operating efficiency and morale of the crews. In addition, he must be capable of directing many unusual procedures related to the availability, procurement, and replacement of those normal and special items of naval and military hardware which are required for effective operations.

In this manner most naval officers eventually acquire considerable practical knowledge of applied, if not pure, logistics and this knowledge is further accentuated by the fact that widely cruising naval vessels inevitably bring their commanding officers vis-a-vis with many knotty problems of detached command. Thus fairly early in their careers, most naval officers have usually had the opportunity of gaining valuable and reasonably sound knowledge of practical and acceptable logistical practices, and by having upon their shoulders the responsibility of a ship and her people under all conditions, or of a naval station,

they have been compelled to develop, in varying degrees, of course, certain healthy military habits of decision and mental flexibility along with a considerable amount of self-reliant resourcefulness.

Therefore, to epitomize the logistics background of the average naval line officer, it would seem only fair to state that, though learning much about the practical aspects of logistics in the normal course of his naval career, he may actually gain but little knowledge of its pure theory. It must also be acknowledged that unless he or the naval service takes timely and definitive steps to remedy this shortcoming, he is quite apt to find himself advancing in rank and responsibility but deficient in his ability to adequately appreciate the fundamental relationships between national economic capabilities, naval logistics requirements, and the gross national war-making potential. Under such circumstances, and regardless of the rank he may ultimately attain, he will probably never achieve a full measure of understanding of the cumulative and often devastating influence which an imbalance of these factors can exert upon naval strategic planning and operations, or of their inevitable, though more remote effects upon our ability to successfully implement any world-wide military campaign plan.

So much for the Navy's broad philosophical attitude with respect to the interlineal position of logistics, its relationship to national economics, its integration with other factors and aspects of warfare, and finally, the chronological evolution of the average naval officer's logistical training and education. With this background the gradual but progressive development of logistics as a specialty within the Naval Service, can be better appreciated and a more accurate assessment made of its potency as a major factor in Naval education, operations and planning.

The impact of the greatest war in history (World War II) upon the world's human and material economy was such as to abolish forever the fatuous assumption, formerly held by some navies and individuals alike, that logistics can be relegated to a minor role in warfare, or that the logistical education and training of Naval officers can continue to be left to the vagaries of chance. The mere contemplation of the late Korean conflict with its continuing repercussions in Formosa and Indo-China and the politico-strategic situation which sired NATO, SEATO, and the recent Franco-German agreement on rearming for the defense of Western Europe, should instantly dispel the skepticism of any who hold opinions to the contrary.

Admiral Robert B. Carney, Chief of Naval Operations, in an address to the General Line School, Newport, Rhode Island, accentuated the fiscal importance of logistics by one of his cogent and inimitable logistics parables, which are always impressive. He stated that: Once a genius with time to spare calculated that in the heyday of the Roman Empire, a single enemy death could be inflicted for the modest cost of about seventy-five cents. In those days military campaigning was indeed both simple and inexpensive. The soldier lived off the land, his sea and land caravans were slave-manned, and his weapons could be handsomely maintained with only a honing stone and some brightwork polish. It has further been estimated that it cost France about three thousand dollars for every enemy exterminated by Napoleon's armies. In World War I, it has been ascertained with fair accuracy, it cost the United States about twenty-one thousand dollars for each enemy removed from the scene. The statistics for World War II are still far from complete but in all probability the cost per enemy killed in this conflict lies between two hundred thousand and three hundred thousand dollars, and this calculation does not attempt to include the difference in exchange rates nor does it consider the cost of living index. If we project such a curve far enough it would appear that the future cost per enemy corpse might one day become fiscally prohibitive.

It now seems pretty generally agreed that the presently existing concepts of warfare, in addition to being influenced by Geo-politics, changing strategic trends, and new weapons systems have, to a considerable extent, been prescribed by national fiscal and economic considerations, and to only a slightly lesser degree by military logistical factors. If this assumption is valid it would certainly seem correct to state, and without much fear of contradiction, that it is indeed a poorly qualified naval commander who lacks the instinctive ability to assess correctly the logistical implications of military operations, the formal education to enable him to assess correctly the logistical implications of military operations, the formal education to enable him to evaluate correctly logistic factors and make acceptable logistical estimates, and the pratical training and experience generally to coordinate and supervise logistic operations.

As a corollary to this, it is believed that no strategist can make an acceptable estimate of the probable outcome of any given course of action without being able to calculate intelligently and weigh all the logistics factors involved.

Although the formal and intensive study of logistics as a science and major subject is a relatively new phase of naval education, the concept of the indivisibility of strategy, logistics, and tactical operations has become so firmly fixed within the framework of Naval philosophy that the Naval War College conducts a logistics course for senior officers, which is on the same academic level and closely integrated with the senior course in strategy and tactics. Despite this, and though most senior officers and students of Naval Warfare admit that the study of the nature and structure of logistics presents a real and worthy challenge, not all of them can agree on an exact definition of Naval logistics, and many of them appear quite uncertain as to just exactly where logistics should fit within the operational framework of the Naval establishlishment, particularly with respect to the degree of importance logistics should be accorded in command structures and relationships.

Despite this modicum of disagreement over the

role which logistics can or will ultimately assume in the Navy, there can be but little doubt of a healthy, and far from languid, awareness on the part of serious practitioners of Naval Warfare, that logistics is in fact a military entity in its own right. Furthermore, there is a definite propensity for most responsible and highly placed Naval officers to admit logistics as a legitimate specialty quite on a parity with strategy, tactics, and operations, those more glamorous phases of the military craft. It is also interesting and reassuring to observe that what amounts to a rather placid acceptance of logistics' role in peacetimes, usually assumes more enthusiastic overtones when a shooting war begins. It is in this environment that hardworking sweat-stained logistics really achieves its full stature and rightful place in the sun. In fact, when the chips are really down, logistics may be truly called the "priceless ingredient" of Naval operations.

It has been previously stated that logistics provides the means for the conduct of war. The means of war, as every military man knows, are men, natural resources, services and materials. In order to have these in the right place at the right time, in peace or war, it is necessary to have advance plans for their training, production, stockpiling and distribution. A military plan like any other scheme, is merely a proposed method of procedure which has been selected to guide some future action. The plan outlines the concepts, the measures, and often the means by which the strategic potentialities of a military decision may be transmuted into the effective kinetics of warfare, and adherence to a chronological sequence of planning is, without exception, the heart of all successful Navy logistics operations. Now before any logical planning can proceed, three basic actions are necessary. First, a suitable objective must have been selected; second, the planner must have comprehensive knowledge and a complete understanding of both the risks and the resources involved in the attainment of that objective; and third, the strategic and logistical concepts must be realistic and harmonious, with the planning concurrent and closely coordinated at all levels of command. Before even a tentative method of procedure or finished plan can be selected, however, the strategy and the logistics implicated in the achievement of the desired military end, must be carefully balanced one against the other.

One constantly finds throughout the entire range of intelligent, purposeful human endeavor, this close and inescapable association between the concept of the objective and the logistical means required for its attainment.

Of such duality is the logical thought process, and it is the only reliable means by which irrational and abortive efforts to solve a military problem can be differentiated from a logical approach.

Actually, this thought process is but the systematic expression of the ever present conflict between the desirability or necessity of attaining a specific objective versus the cost incident thereto. It is the same natural and almost unconscious formula that we humans employ daily in solving our own basic personal equations.

If the foregoing conclusions are valid and acceptable, then one may correctly state that all operational planning of any consequence must be biphasic and concurrent; the strategic phase portraying the design and desirability of the operation, and the logistical phase portraying the means and cost of its support.

This, then, is the natural process for all military operational planning, great and small, and other things being equal, the one most likely to achieve the best results.

From all of this, one is impelled to conclude that the most successful Naval staff will be the one in which the closest cooperation exists between its planning, operational, and logistics elements.

While on the subject of Naval staffs, it seems appropriate to say a word about the Staff Logistician. In the Navy, it is believed that a proper logistics officer should never be guilty of saying "logistically impossible" to any finished plan the staff may have made. Why? Because he should be so thoroughly trained in the making of sound and timely estimates, so well educated in specialties of his field, and so endowed with that priceless commodity, common sense, that he will be able to influence so rationally the staff thinking that the planning at every stage will be conducted along feasible lines.

Having made homologous twins of operations and logistics and established their consanguinous relationship with strategy, we will now briefly consider the broad general aspects of the organization which is set up for Navy logistics planning and operations.

This we can begin with a brief and perhaps somewhat over-simplified sketch of the normal chronological flow of Navy logistics planning which has its inception in the Joint Chiefs of Staff. In the organization for National Defense, the Joint Chiefs of Staff under the Secretary of Defense are basically responsible for overall U. S. Military strategy and for the preparation of the strategic and logistics plans to support all formal military commitments and international aspirations. Flanking the Joint Chiefs of Staff, and on the same level, is the Assistant Secretary of Defense for Supply and Logistics, whose organization furnishes overall direction for military procurement, production and distribution.

When the Joint Chiefs of Staff assign a task to the Navy through the Chief of Naval Operations, it is assumed by him that such a task has been thoroughly tested for feasibility and is logistically sound. However, before the Chief of Naval Operations further translates any assigned task into the more substantial terms of forces, he requires his own logistics organization to test again the assigned mission for feasibility. This is done in order to be doubly certain that the required Naval forces can be logistically supported under prevailing or extrapolated conditions. By this device, he reassures himself that his proposed task

organizations are logistically sound and the projected operations logistically feasible.

Operating both in peace and war, the Navy life cycle is susceptible to a certain sequence of major events, viz: peacetime operations, mobilization, active warfare, demobilization, and then back to peacetime, or, as at the present, to quasi-peacetime operations. Each of the above phases requires its own special type of logistics planning, with each such phase having certain limiting factors. For example, in current peacetime operational planning, the principal logistical limitations are ordained by appropriations, while in war these limitations are found to be in men, materials, and in the lead time required to obtain the finished end items of warfare and deliver these to the operating forces. Navy logistics planning, then, is divided into the phases just mentioned, each phase reflecting one of the major situations likely to be encountered, that is, peace, mobilization, or war.

With this admittedly sketchy outline of high level logistics planning as a point of departure, we can now move on to a consideration of logistics at the Fleet level. Inherent in the broad missions assigned to each of the major Fleet Commanders, is the general responsibility for the logistical support of all their assigned forces in peace or war. They also have certain additional specific logistic command responsibilities, the implementation of which requires that their staffs conduct current peacetime, mobilization, and long range planning operations, the latter having as a starting point the actual wartime mobilization of our Naval power.

Current or peacetime planning is always the more arduous task, as logistical limitations then become painfully apparent for the good and logical reason that it is always more difficult to justify military operating costs to an economy minded Congress when the psychological impetus of wartime motivation is lacking. Most bright staff ideas and all operational training calls for money, and in peacetime there is never enough of this available. However, such a situation does produce at least one salutory effect, to wit: it sharpens the logistician's wits and planning acumen upon the very harsh and abrasive grindstone of reality. This experience is invaluable and is sure to stand him in good stead, especially in wartime.

Let us now pass to the logistics role in Fleet Commands, by observing the broad logistical considerations which invariably appear in their organization and operations. Upon assuming command each Fleet Commander devises a "task organization," which includes such logistic support commands as he considers suitable for the execution of his assigned mission. The Fleet Commander then assigns to each of his major task force commanders, certain specific missions or tasks which are usually couched in rather broad terms, and which these commanders normally use as a basis for formulating the more specific plans and tasks for their subordinate forces, which usually embody logistical elements.

An overall analysis of these tasks and operations, which must be tested for logistical feasibility at every level, will discloses the total logistical requirements necessary for their implementation.

To effectively carry out his logistics responsibilities, the Fleet Commander arranges the fleet units in groups by ship type. These are called Type Commands, and each is under a Type Commander for purposes of administration and routine maintenance. Three of these type commanders have primary logistics responsibilities which extend beyond their own organizations. These are: Commander, Service Force; Commander, Naval Air Force; and Commanding General, Fleet Marine Force.

In order to establish a structural framework for reference and discussion of fleet logistics, it is imperative that one clearly recognize the difference between logistics per se, and those organizations which must be established to effectively manage logistics problems and carry out logistics functions.

Therefore, whenever one encounters any logistics task or equation, it will always contain certain inherent and elemental constants, which we shall call the "basic elements of the logistics problem." They are: the determination of requirements, procurement, and the distribution of finished products to the ultimate user. These are all familiar processes and well known to experienced commanders. On the other hand, the solution or implementation of a logistics plan or operation, requires that full weight and consideration be accorded certain basic aspects of the logistics problem. These are organization, planning, execution, and supervision, and regardless of the scope of a logistics task, problem, or operation, these elements and aspects are invariably involved, closely related, and always blended. For example, lower echelon procurement must depend upon the capabilities of higher echelon distribution, and both of these are dependent upon the prior determination, and a timely statement of requirements. A concrete example of the above is the Navy supply system. This, as we all know, is a vital, complex and extremely flexible organization, very responsive to Naval requirements and which is itself a curious combination of requirements, procurement, and distribution.

There is such a marked degree of mutual interdependence between determination of requiremnts, procurement, and distribution, that not one of these basic functions can long operate without the support of the other two, and no logistics problem can be successfuly resolved without a reasonable understanding of the military implications of each. Take the determination of requirements, the first equation of the logistics problem and the first step in its solution. This requires a dual and vertical approach.

One approach considers current operational needs and has its origin in the smallest units of a force. The logistical requirements of these units which are based upon accepted operational concepts and usage factors are ascertained, compounded, and sent upwards through all echelons of command until a composite statement of the total fleet requirements finally

emerges at the high logistical levels at which the national and international requirements for the conduct of either limited or global warfare are resolved. The other approach, however, which is for future or long range operations, is the exact reverse of this. It begins at the highest levels, where national objectives and the strategy envisioned for their attainment must be known before any realistic determination of logistics requirements can proceed, and ends when these national strategic concepts are translated into military campaign plans.

It is imperative that all commanders constantly keep in mind the time-honored truism: that upon the accurate determination of future requirements and their relationships to available military resources, rests the final decision as to the type of war we must fight. For, national objectives generate national policy, which in turn dictates national strategy. This is only part of the picture, however, for although the pursuit of a particular strategic concept may appear most desirable, this may not be possible unless the logistical requirements and their national economic implications have been fully weighted and found to satisfactorily meet the final test for feasibility. Because of these facts it is believed correct to state as a fundamental military principle, that the determination of requirements is a responsibility, function, and prerogative of command.

Procurement, the second basic element of the logistics problem, is firmly sandwiched between the determination of requirements and distribution, and it is also the one point at which military logistics, the civilian economy, and the total national war potential become tangential. Procurement is erroneously believed by many to be predominantly a supply function, which indeed it does resemble in some respects, particularly with regard to the low-level resupply of standard items. This is fallacious, however, as the broad field of procurement far transcends its supply implications and its almost endless military-economic ramifications are so vast and complex that its understanding requires a lifetime of study and effort by many of our most able industrial, economic, and Naval leaders.

One needs only to contemplate the enormous quantities and infinite variety of complex weapons of modern warfare to appreciate the magnitude of the effort in research, planning, and production that is necessary to deliver to our combatant forces the right weapons in the right quantities, at the right place, at the right time.

Distribution, the third major element of the Navy logistics problem, begins with the accumulation and "stockpile" storage of personnel and materials, and ends only when these are actually placed in the hands of the operating forces. Distribution, like the determination of requirements, is also a command responsibility. Much of the activity classed as distribution is closely integrated with the procurement, storage, and issue of all types of logistic support to Naval shore activities as well as to the forces afloat. To adequately fulfill the peculiar demands of the operating forces, the Navy has successfully developed and exploited three basic and very necessary characteristics which are germane to any really reliable distribution system; they are: economy, flexibility, and responsiveness. These three characteristics, when kept in proper balance and relationship with the elements of sound distribution, accumulation, storage and transportation, should so blend and mutually support each other, that each element or characteristic will act as an effective and almost automatic system of checks and balances upon the others.

To fully comprehend the phenomenon of the Navy's distribution system, and it is phenomenal, the reader must first thoroughly understand and accept the fact that for the Navy, the logistic support zone includes the entire theatre of military operations. One must always keep in mind the fact that there is no Naval equivalent to the Army's communication zone logistics organization, because in a strictly Naval, or "sea" theatre of operations, the combat area and communications, or logistic support zone, are to all practical purposes indivisible and must be regarded as one.

This is all the more easily understood when one considers that literally and figuratively, the essence and principal characteristic of a fully developed Naval offensive, is a high degree of tactical fluidity, making rapid movement over vast ocean areas possible. We thus see that the combat and communication zones are continuously blending and shading one into the other. Actually they may only be separated by such ephemeral factors as time and space, and by the cartographic boundaries of latitude and longitude.

Because our operating forces are ranging over the greater portion of the earth's surface and are frequently separated from their shore bases for extended periods, the Navy's distribution system, in addition to other factors, must contain the "built in" capability of providing a fully mobile type of logistic support to the forces at sea.

To give this support, the Navy's distribution system, which also includes Fleet Logistics Air Wings, has been so tailored as to provide the operating forces with everything which they require to carry out their assigned missions, while at the same time, giving full consideration to certain advantages and disadvantages which are inherent in the media in which they must operate. Happily, the Navy has evolved a distribution chain which has thoroughly demonstrated this capability and which, since all our Naval strength originally emanates from the shore, begins at the coastal continental shore establishments. From here the logistic support chain extends outward to extra-continental shore bases, then further on to the floating advanced bases, finally terminating in the highly mobile and flexible logistic support ship types, which are capable of rapidly delivering large quantities of practically all types of materials to the combatant forces at sea. In addition to their other special characteristics, these logistic ships have steaming capabilities which permit their employment as high-speed

replenishment vessels even in critical combat situations.

The simultaneous and complete mobile replenishment of assorted types of Naval Units underway in a combat zone is perhaps the most unique and certainly a spectacular aspect of low echelon Navy distribution. Before reaching its present highly organized and efficient state, it passed through several complex metamorphic phases, and although the complete pedigree of mobile replenishment is not known to the writer, it can probably be said with considerable assurance that the oil-fired marine boiler was its most proximate direct ancestor. The exchange of vital supplies between ships at sea is as old as the earliest recorded maritime history, but the early underway refueling operations conducted by the U. S. Navy were the real harbingers of the present concept of total mobile logistic support at sea.

This novel technique is an almost exclusive development of the United States Naval Service, and a demonstration of this capability of quickly replenishing groups of fast-steaming Naval Units is an impressive spectacle, which once seen is not soon forgot, especially when such operations are conducted under combat conditions. One need only to contemplate the Okinawa Campaign, in which the carriers of the Fifth Fleet were kept fully supplied by this method throughout seventy-nine consecutive days of sustained, strenuous and successful combat operations, to fully comprehend the impact which this concept will exert upon future Naval warfare.

In spite of all efforts toward a peaceful co-existence with Russia, or the treaties which have been formulated for Western Mutual Defense, the tyranny of the ticking clock of international tensions and conflicting ideologies seems to forebode an ever increasing tempo of all phases of warfare. In such a climate of tension there is every reason to believe that there will be future sea offensives which will continue to move with ever increasing rapidity. This is due not only to the new weapons systems now available, but also to the multiple tactical redeployment of forces demanded by global strategy and the new types of fuel soon to be available for sustained high speed propulsion of Naval vessels. The inexorable trend toward such a situation already appears to be making infeasible the construction of large fixed type extra-continental Naval storage facilities. Therefore, for these and other reasons, a decision to build even a minor base can never again be made without a careful, and I might well add, a prayerful analysis of its mission and vulnerability.

An experienced Admiral, seasoned in the lore of farflung Naval Warfare once said, "You can't move an island or land base once it's built. It will stand exactly where you put it in full view of military posterity who may regard it with awe or derision, depending upon how well it fulfilled its mission." The Admiral further postulated this corollary, "When following a fast-moving front, keep your supplies in ships when possible; for, if you don't like one anchorage, you can heave around and steam to another without leaving a hole to mark the spot where you made a wrong guess."

For these reasons it will undoubtedly again become necessary to employ suitable types of floating facilities at advanced bases from which fast-steaming shuttle ships can transport all of the logistical imperatives to the combatant units at sea.

Imitation is still recognized as the sincerest of flattery, therefore, it is hoped that the writer will not be regarded as chauvinistic in pointing out that in borrowing the Navy-developed concept of mobile logistic support and adapting it to their own operational needs, the Air Force in air to air refueling operations, which must surely be expanded to include transfer of personnel and other logistic items, and the Army-Marine efforts to develop practical doctrines of air logistic support and air redeployment for field units committed to tactical operations of rapid movement, are both complimenting and handsomely repaying the Navy for its pioneering efforts in this novel sphere.

In closing it might not be amiss to make this terminal observation: Despite the current plethora of military study and research, the wide variety and incessant improvements in the power, lethality, and automaticity of weapons systems, and the application of electronic "brains" to the solution of Naval logistics problems, it still appears that one irreplaceable component, the man of trained mind, practical sense, sound experience, pride and love of his Service, and a well sharpened pencil, will continue to be the ultimate factor in the logistics equation and in naval warfare for a long time to come. He is still the one irreplaceable component of military success.

JOURNAL OF THE FRANKLIN INSTITUTE

INCREASING INVENTIVE CREATIVENESS

ACKNOWLEDGEMENT

The author of this article was C. D. Tuska, Director of Patent Operations, RCA Laboratories. It was published in the August, 1955, issue of the "Journal of the Franklin Institute."

INVENTIVENESS per capita per year in the United States, measured by patent applications, shows a peak after World War I and thereafter a decline of about 40 per cent. The inventive rate, on a similar scale, in Great Britain is only down one-sixth from the 1928 peak. Furthermore, the per capita patent applications in Great Britain now exceed the United States. Germany's per capita patent applications in the early 1940's were down about 50 per cent from their 1930 peak which exceeded United States and Great Britain.[1] I do not have the latest figures for Germany. While I do not know what effect the division of Germany may have, I expect that the recovery noted in other fields also applies to invention at least in Western Germany (see Fig. 1).

A Bill (H.R. 4267) recently introduced in the Congress by Representative Hosmer proposes that a Commission be established to investigate and study our patent laws. The Commission is to determine "what changes . . . are necessary . . . to promote a greater contribution to continued technological advancement by the United States, with particular regard to the problem of how to stimulate an increased contribution on the part of the individual inventor." Let us hope that the proposed Commission does not conclude that an increasing *number* of U. S. Patent Applications means that we do not have a falling rate per capita. In these times of international stress, I believe, we should be concerned with relative international rates, and especially with our own declining rate.

[1] These figures do not exactly indicate the national invention per capita rate for the United States, Great Britain or Germany, because in each case foreign origin patent applications are included.

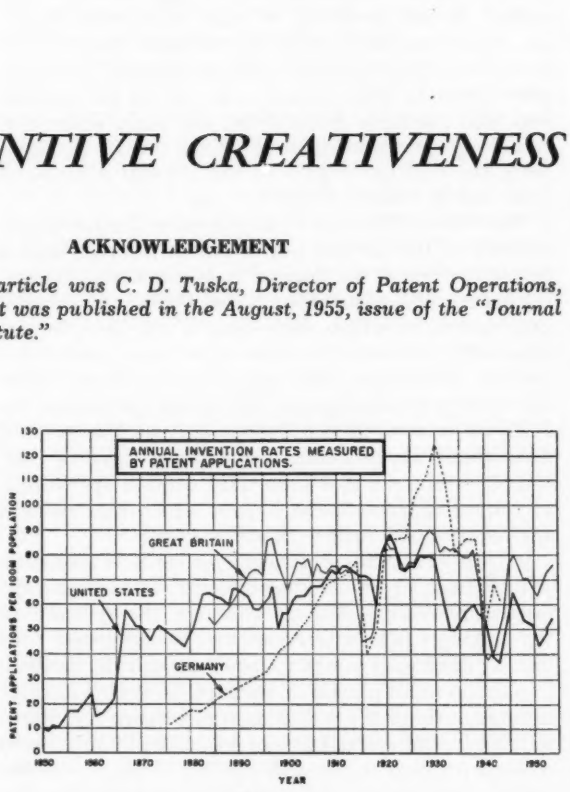


Figure 1.

Now that I have pointed out that quantity of inventiveness appears to be falling, I do not plan to use much space looking for explanations. Neither do I propose to blame the Republicans or the Democrats because most of us are one or the other or neutral so in the final analysis it is our own fault. Rather than complain I want to illuminate a few spots. Some of the crannies may be obvious, some may be obscure, some may be forgotten, but there is always the chance that my shots in the dark will start you on a path to invention. Only one thing do I promise: I shall not make your inventions for you.

ADVERSITY

Most of us have heard or read "necessity is the mother of invention." According to my theory adversity helps too. If my theory is correct, the curve for Germany should take, or probably already has taken,

an upward trend. Anyway, apply the adversity theory and you'll find that not a few inventions were begat under that kind of stress. If you demand examples, study Morse's invention of the telegraph, Bell's telephone, Goodyear's vulcanization of rubber, Holland's submarine, and there are surely many more. Please do not think I advocate poverty, ill health, or any other misfortune just to advance invention. You may have adversity in the form of apparently insoluble problems at home. Direct your mind toward invention. Not only will mental concentration in another field lighten your burdens, but you may make a discovery or invention of great merit.

SERENDIPITY

That tinkling word was coined by Walpole. It means the gift of finding valuable or agreeable things *not sought for*. Serendipity is certainly a happy state of being when it leads to invention. In seeking a super high frequency amplifier do not let surprise brush away a discovery of a very stable and powerful super high frequency oscillator. True, you were not looking for the latter, but be sagacious enough to examine what you found. There was plenty of serendipity in Thomas Edison for I believe that it was that state which brought him to the phonograph. Don't overlook what you were not seeking!

CURIOSITY

The word "curiosity" has a connotation implying meddlesomeness. "Curiosity" herein has the sense of "careful attention" and "disposition to inquire." Newton's formulation of the laws of gravity may have been started by curiosity. Don't you suppose that curiosity was the important factor first in Zacharias Janseen's and later in Anton Leeuwenhoek's inventions of the microscope? Perhaps it was an ingredient in the invention of the stethoscope. If you would invent, be curious! When you observe the unusual, ask yourself "why?," not "so what?" Furthermore, you may not observe, unless you pay careful attention. Nature has a way of sometimes hiding her secrets; pry into them. Cultivate scientific curiosity!

NONIMITATIVENESS

If you would invent, be nonimitative. The important discoveries and inventions are more apt to occur when exploring a new path. Be sure to keep your mental scouts alert. Do not travel an unchartered path so fast that the scouts can not, *on proper occasion*, mentally trod an attractive byroad. Even a "dead-end" street could have a treasure at the end; then perchance it may not be a dead end. T. Brown seemed to express the point when he wrote: "Not picked from the leaves of any author, but bred amongst the weeds and tares of mine own brain." Avoid imitation—it stifles invention!

[2] Nations Business, February 1955, pp. 28-30 and 100.

SYNTHESIS

In a recent article[2] "Here's How to Train Your Own Inventors," Richard Gehman identifies two approaches to solve a problem—analysis and synthesis. He then defines synthesis as "a solution that is based on hunch or intuition." Gehman's article states that the analytical approach "examining each aspect step-by-step" rarely leads to creation. Felix Morley, in the same publication, while discussing the problems of personnel and public relations writes ". . . and where solutions will not come out of test tubes, or off drawing boards, mere technical efficiency sometimes seems more of a handicap than an asset."

It may be true that a symmetrical scientific training may discourage invention. One who foresees only all of the difficult technical difficulties can too easily conclude that the problem at hand has no practical solution. However, many with all the essential scientific facts tucked away in their minds can, sometimes without conscious effect, emerge with an almost complete solution of a baffling problem. You can call it synthesis, intuition or hunch. Distinguish it from analysis, if you wish, but do not overlook the mental process of "forgetting the problem for awhile." If you do, you may suddenly be surprised by having a workable, ready-made invention pop out of your "unknown" mental excursions. In urging that you be mindful of the "subconscious" approach to invention, please do not get the notion that I am against excogitation, for I am not.

RECOGNITION OF THE PROBLEM OR THE NEED

Dr. John M. Miller, who was awarded the Institute of Radio Engineers Medal of Honor in 1953, once told me that recognition of the problem was not infrequently the royal road to invention. If the problem is stated very clearly, the solution may come almost automatically. Recognizing an unsatisfied public need for a particular device, can often inspire one to make the required invention. When we have the clearly stated problem or have visions of the desirable but unavailable article, the mental approach may be analytic or synthetic. Apparently the patent conscious inventor need not be too concerned as to the manner[3] in which he made the invention. Anyway, see whether you can't recognize some problems or needs, and then persistently seek the solution.

THE HAPPY ACCIDENT

When Robert Burns wrote: "The best laid schemes o' mice an' men gang aft a-gley," he did not have in mind a "happy accident." But I say to you, when your experiments "gang aft a-gley," most carefully examine the unexpected, and even the undesired. Therein you may find "a happy accident" or a great invention. Serendipity, curiosity, and sagacity should join hands if you are to discover something important in the failures to reach the original target of your quest.

[3] ". . . Patentability shall not be negatived by the manner in which the invention was made." 35 USC 103.

Recently Dr. Harry Olson, a neat inventor if you ask me, recited that he was hard at work on his ribbon or velocity microphone.[4] He did not understand why the rear response was practically non-existing. He had expected a non-directional response pattern. Searching for the cause he found that the mechanic in building the model had failed to cover a hole. A finger over the hole clearly demonstrated the error.

Many might have remedied the mistake and moved on to the desired result. Dr. Olson not only found the cause but recognized the invention or discovery of an improved microphone[5] in which the response pattern could be readily changed. It takes a sagacious inventor to recognize and to profit by the happy accidents.

Charles Goodyear said it this way: "I was encouraged in my efforts by the reflection that what is hidden and unknown and cannot be discovered by scientific research, will most likely be discovered by accident, if at all, by the man who applies himself most perseveringly to the subject and is most observing of everything related thereto."

Perhaps you would like another example of the "accidental" invention. My good friend P. H. Spencer, the inventor son of a Yankee inventor of great note, suddenly realized that tomorrow was his child's birthday. He had forgotten to buy a present. The stores were closed. He hastened to his shop and equally hastily conceived and hurriedly built a rubber-band powered toy ornithopter. The device was presented and the unexpected happened: it actually flew and attained an altitude higher than its launching point. Spencer then decided that he had something. He reasoned that if he carefully constructed a second model, it would perform better. The second model was made with all the precision he could command. The well constructed model failed to fly!

After recovering from the surprise Spencer started to reason, and to compare the precise model with the earlier model. He discovered that the first model had included, albeit unintentionally, misaligned pivots or bearings for the main wing spars. The misalignment caused the wing to sweep to the rear on the up stroke and forward on the down stroke. This wing motion, quite by accident, produced "lift." In the precise model the wings simply rose and fell but did not lift. Spencer had made a discovery—a patentable invention.[6]

[4] Olson, U. S. Patent 1,885,001, "Apparatus for Converting Sound Vibrations into Electrical Variations."

[5] Olson, U. S. Patent 2,301,638, "Sound Translating Apparatus."

[6] Spencer, U. S. Patent 1,907,887, "Toy Aircraft."

IMAGINATION

Thus seven circumstances of invention have been characterized. Doubtless there are many others. Also mere circumstances are not sufficient to foster invention. Invention requires something more. Some mental act must be applied. The invention must be "conceived." Let us avoid problems of psychology and semantics by calling the mental act "imagination." You may protest that you don't possess imagination. Most children have it to a high degree. You may not have cultivated it but you certainly have not lost it. Emerson wrote: "Imagination is not a talent of some men but is the health of every man."

I could write at length on constructive imagination, creative imagination, productive imagination, and many other forms of visionary thinking. Fortunately, that is not necessary because I can refer to "Applied Imagination—Principles and Procedures of Creative Thinking" by Alex F. Osborn. Read this recent book or one of Mr. Osborn's earlier works if you would awake or stimulate your imagination.

CREATIVE IMAGINATION x PROPER EFFORT = SUCCESS

Favorable circumstances, and an abundance of creative imagination will surely help invention. I will even throw in luck, but I am sure I have not named the essential ingredient. Unfortunately, I do not know the word for it. A recent newspaper article stated that Dr. Harrison G. Gough, a research psychologist at the University of California, discovered a way to test for "it." He tackled the problem—"why some gifted persons make a place for themselves in the world and why others with equal gifts wander aimlessly and let their gifts go to waste." Dr. Gough provided the name "psychological persistance." However, I shall call the essential ingredient "effort."

Frequently the difference between a success and failure in invention is "effort." Surely few inventions are born without effort. You may go through all the mental steps, but do no more, and your invention will die aborning. An invention, if it is to have the slightest patentable significance, must be disclosed to others. That takes effort. The disclosure should be in writing. That too takes effort. Constructive reduction to practice, that is, filing a patent application, takes more effort. Actual reduction to practice takes still more effort.

Perhaps a summary in algebraic equation form might be helpful:

(Surround yourself with favorable circumstances) + *(Exercise creative imagination)* × *(Apply effort . . . + apply effort^n)* + (*k*, where *k* = good luck) = One approach to invention.

REAR ADMIRAL HYMAN G. RICKOVER, USN

NUCLEAR POWER AND THE NAVY

THE AUTHOR

is Chief, Naval Reactors Branch, Division of Reactor Development, U. S. Atomic Energy Commission and Assistant Chief of the Bureau of Ships for Nuclear Propulsion, Navy Department. Although this article was presented as a talk to the San Francisco Council of the Navy League and has been given some distribution by the Navy League, we feel that it should be made directly available to the members of the Society. In consideration of the position and accomplishments of the author there can be no doubt that this is a basic document in the recorded history of nuclear power. For these reasons we asked Admiral Rickover for permission to publish it in the JOURNAL. *He granted this readily.*

NOTE: *The editor regrets that the urge to rush this paper to the printer to prevent its delay to the next issue, prevented obtaining a full biography of Admiral Rickover.*

I APPRECIATE this opportunity to talk to you on Theodore Roosevelt's birthday because he, more than any other man, helped to mold our Navy into a highly mechanized and effective instrument of national policy. In particular, he encouraged the Navy to convert from coal to oil. Although the use of oil as a fuel for our warships had been under consideration since 1866, it was not until his administration, and with his encouragement and support, that the final decision to change was made—a change almost as significant as the one from sail to coal.

Today our Navy is embarked on an even greater change—from oil to nuclear power. I don't believe this will take as long as it took to convert from sail to steam or from coal to oil. Unlike the earlier changes in which merchant shipping took the lead, the change to nuclear power began with a naval vessel. Furthermore, the generation of nuclear power in significant quantities took place, for the first time, in the atomic engine of the land-based prototype of the *Nautilus* in Idaho.

Before I discuss the impact of nuclear power on the Navy, I would like to give you my idea of two of the basic principles of waging Naval warfare:

One—Keep the potential battlefield away from the community centers of the United States and her allies. This calls for an ability to mount a self-sufficient and sustained operation. It calls for the ability to strike well within the enemy's borders, and to counter the return blow well away from our own borders or those of our allies.

Two—Keep the position of the launching point undisclosed. This requires mobility, and a denial to the enemy of intelligence concerning our intentions.

Various types of naval vessels are used for accomplishing these concepts. Stated simply, a naval vessel is a mobile platform for firing shells, for launching planes and missiles, or for sending or receiving men, munitions, fuel, and intelligence. This platform can be on the surface or below the surface of the ocean. The missiles can be shells, or rockets, or they can be guided. They can be fired directly from a gun, from a launching device, or from an airplane which homes on the floating platform. The naval airplane is thus an airborne device which extends the range of the parent platform.

In the days of sail, men-of-war had limited cruising radius, but they were bound to the surface of the ocean and were dependent on wind and weather. In other words, they could go *anywhere* but not at *any time*.

Coal and oil freed naval vessels from dependence on wind and weather; and the storage battery allowed them to go underwater. However, they could no longer cruise indefinitely; they had become tied to fueling stations—either fixed or mobile.

Nuclear power combines the advantages of sail with those of fossil fuels. We can now go *where* we want, *when* we want.

It is thus clear that we can now have platforms which we can move on or below the surface of the sea, and which are self-sustaining in fuel.

The ultimate objective in the development of nuclear power for naval vessels is the nuclear powered task force, capable of remaining at sea indefinitely without refueling. Such a task force has become possible by the proved use of nuclear power for submarines and its imminent use in surface vessels. It is not too difficult to visualize the naval task force of the future.

Such a force will consist mainly of large aircraft carriers and multi-purpose escorts capable of launching defensive guided missiles against enemy aircraft and guided missiles.

Their escorts will be equipped with devices for submarine detection and destruction.

Such a force will be almost entirely self-sufficient for long periods of time, requiring resupply only of ammunition and provisions at relatively long intervals.

The striking power of such a force would be many times that of the World War II aircraft carrier task force, with but a small fraction of the ships being necessary.

Nuclear powered submarines would operate in the vanguard, serving as scouts, missile carriers, and radar pickets.

Such a force will be widely dispersed over an ocean area as large as the State of Maine, and would be able to control an area of 60,000 square miles.

An enemy vessel or aircraft which approached that area would have small possibility of survival.

Of course such a sea base is not absolutely invulnerable against every form of attack.

The unpleasant fact of nuclear war is that everything is vulnerable, including airfields ashore. But I believe that a mobile sea base has a far greater chance of survival than a fixed land base.

The mobile sea base possesses many inherent advantages:

First, it enjoys unobstructed radar vision.

Second, the location of the sea base cannot be predicted. Its location will not be secret, but it will be difficult at any particular time to determine the exact position of any particular unit of the force.

In addition, the task force defense system will limit the possibility of extensive enemy reconnaisance.

Third, the offensive potential of the sea base will be used to stop enemy attacks at their source—the enemy's bases—by using the overwhelming concentration of airpower which will be available to the task force.

We will always know the location of his fixed bases, while the enemy can only guess at the whereabouts of our task force vessels.

To give you some idea of the advantages of nuclear propulsion, let me tell you what the *Nautilus,* our first nuclear submarine, has already done.

On December 30, 1954, the *Nautilus'* plant was started up for the first time. Four days later it was developing full power alongside the dock. Then on January 17, 1955, she put to sea, and within six days she had completed a grueling series of sustained high-speed test runs, which included more than fifty dives. As of today she has steamed more than 23,000 miles, more than half of which has been fully submerged.

An early cruise of the *Nautilus* in the Caribbean was a history-making event. I am privileged to be able to reveal to you some of the facts:

On this cruise, the *Nautilus* steamed totally submerged from New London, Connecticut to San Juan, Puerto Rico—traveling a distance of more than 1,300 miles in 84 hours. This broke a number of long standing records.

First, this was the greatest distance, by a factor of ten, ever steamed, completely submerged, by any submarine.

Second, her average speed for the entire trip was about 16 knots—the first time any submerged combatant submarine maintained such a high speed for more than one hour.

Third, this was the longest period that any U.S. submarine cruised completely submerged.

Fourth, this was the fastest passage ever made betwen New London and San Juan by a submarine of any type, traveling either surfaced or submerged.

This cruise of the *Nautilus* has demonstrated that all previous concepts of the length of time required by submarines to reach distant patrol areas must be drastically revised.

Conventional submarines are really surface vessels capable of operating submerged for short periods of time. The *Nautilus* is the first true submarine, and was designed to steam faster underwater than on the surface.

Contrary to early misconceptions, the *Nautilus* is not just a floating demonstration of the feasibility of nuclear propulsion for naval vessels. She is a working combatant vessel, fully capable of waging offensive warfare. Her propulsion plant supplies power equivalent to the electricity consumed by a city of 20,000. Her nuclear reactor furnishes all of her power needs—lighting, heating, air conditioning, cooking, movies.

She is equipped with the best available torpedoes, sonar, fire control, radar, and other military devices required by a modern submarine. Her power plant was built to fully withstand the rigors of war service. In fact, we requested, and Congress authorized us, to test to destruction a fleet submarine, the *Ulua,* by means of depth charges, in order to determine the adequacy of the *Nautilus'* propulsion equipment under extreme conditions of shock.

The meaning of the *Nautilus'* performance is now plain. The whole science of anti-submarine warfare has been based on one premise—that the submerged submarine is powered by a storage battery that must soon exhaust itself—quickly at high speeds, and in about forty to fifty hours at the lowest speed. Destroy this premise—as nuclear power has done—and the

whole business of hunting and destroying submarines must be completely revised.

The *Nautilus* is not merely an *improved submarine*. She is the most potent and deadly submarine afloat. She is, in fact, a *new weapon*. Her impact on naval tactics and strategy may well approach that of the airplane.

It is obvious that a major advantage of nuclear power for any naval vessel is in logistics. The cruising range and strategic value of a warship have heretofore been limited by the amount of fuel it could store in its hull. When its fuel supply is depleted, a conventional ship must turn to a fueling ship or a fueling station. Refueling operations are time consuming, hazardous, and reduce the ship's effectiveness. During World War II the Navy succeeded in operating mobile refueling bases which were able to follow task forces. The striking power of the fleet was thus extended, but only by providing it with an endless chain of tankers.

Nuclear ships will have virtually unlimited cruising range, even at high speeds. No refueling facilities will be required to replenish their propulsion fuel. This will be done routinely as part of a regular scheduled overhaul. Consequently, the construction and overhaul facilities heretofore required to service these tankers and their equipment will be reduced. Also, fewer escort vessels will be needed to protect the remaining tankers. Personnel now assigned to man such fleet support ships and their shore facilities will be released for other purposes. All of this will result in less drain on our manpower during war time—and manpower is the factor which ultimately limits a nation's war potential.

For example, we are presently, for the first time, refueling the land-based prototype atomic engine of the *Nautilus*. It has been in nearly continuous operation for two and a half years without refueling. This plant and that in the *Nautilus* are our first ones and we call them our "Kittyhawk" models. Our aim is to design nuclear power plants which can last for an entire war without being refueled.

Another advantage of nuclear power is that the fuel requires no oxygen. For the first time we are not dependent on the earth's atmosphere for combustion of fuel. The significance of this can be understood when it is realized that a large naval vessel consumes 600,000 cubic feet, or 20 tons, of air to burn the more than one ton of fuel oil required each minute at full power.

In a conventional ship, supply ducts lead the air to the boiler spaces. Other ducts and stacks remove the gases resulting from combustion. Altogether, these ducts take up a great deal of volume on the upper deck levels, space which could be used for other purposes in nuclear powered ships. The rupture of exhaust ducting during battle can spread fumes throughout the working area below decks.

For aircraft carriers nuclear power offers additional advantages. Space now used for fuel oil can be used to carry large quantities of aviation fuel, ammunition, and other supplies. The carrier will thus be able to support many more hours of aircraft flight, and its military capabilities correspondingly increased. Also, stack gases are a fume hazard to personnel and to the handling and operating of aircraft on the flight deck. With nuclear power these hazards are eliminated, and better arrangement of the upper decks for aircraft operation is made possible.

Think what the use of nuclear fuel will mean from a storage standpoint. We will be able to store the replacement fuel required for all of the Navy's nuclear powered vessels in a few large buildings. Nuclear fuel is not radioactive and it does not deteriorate. It can be manufactured and stored indefinitely during peace time. Should it not be required for naval purposes, it could be converted to use in shore atomic power plants.

The question is frequently asked, "How was the development of the *Nautilus* brought about so rapidly?" This is a natural question because the time normally required for military items from inception of the idea to delivery on a scheduled date takes seven years for a new design jet fighter plane, six for a new design bomber, five for a destroyer, four for a rifle, and three years for a new uniform.

It took four years from the inception of the idea of the *Nautilus* until her shore-based prototype was in operation. Two and one half years after her keel was laid the *Nautilus* was at sea. Bear in mind that we had to design, develop, and build not only a nuclear plant, but also the first steam plant ever to propel a submerged submarine. There was hardly an item we could find on the shelf; almost everything had to be designed and developed for the specific purpose.

The answer to the question is, of course, the obvious one—people, hard work, and attention to detail. Some may believe that projects such as the *Nautilus* emerge from routine organizations, systems, or established procedures. Our experience with the *Nautilus* shows that none of these lead to really significant results in development work. A project like the *Nautilus* calls for dedicated people who do not permit obstacles to stop them. Unusual things are not accomplished by usual methods.

It is doubtful that the *Nautilus* could have been developed in so short a time had it not been for the unique governmental relationship which permitted one group of people to have full responsibility, both for the Atomic Energy Commission and the Navy.

This joining of a civilian with a military agency has been a remarkable success. The freedom to operate within both agencies without the burden of liaison or layers of intermediary groups saved much time and manpower. And since it takes time to spend money, the cost was also reduced.

This unit operating for both the Atomic Energy Commission and the Navy has established so close a relationship with the industrial and ship-building organizations who design, develop and construct nuclear power plants and ships that, in effect, the entire operation has become a single, integrated effort. I know of no similar large-scale project in the United States where the relationship among all the parties

is as close. I commend this method to others who are charged with developments of similar magnitude.

For our group to be permitted to operate in this manner required a great deal of tolerance and understanding by the people of the Atomic Energy Commission. And I would like to pay tribute to them, and particularly to our Chairman, Lewis L. Strauss, for their constant help and for the use of the Commission's personnel and laboratories.

Another reason for the rapidity with which our program has proceeded has been the full support given by Congress, especially by the Joint Committee on Atomic Energy. Three members of this Committee are from California. Senator Knowland and Representatives Hinshaw and Holifield have all personally assisted from the very beginning.

And another Californian, Charles S. Thomas, Secretary of the Navy, has constantly supported and helped the nuclear program. He has continuously emphasized the profound impact of nuclear power on the Navy and the need to attract to it and train our best civilians, officers, and enlisted men.

In our work, as in every venture, trained people are essential. In the early days, and over the protests of my leading people who did not want to interrupt their work, I sent many of them, and also our new young people, away for advanced technical training in nuclear engineering. At the time it seemed the wrong thing to do because of the extremely heavy work load. But we knew that we had to develop many technically qualified people if we were to become an effective organization. Similar educational steps had to be taken by our contractors. Those of us who remained behind had to carry the burdens of the ones who went away to learn, but we became the stronger for it. The benefits from this technical training convinced me that it should be continued. As a result, nearly everyone who has joined us since the beginning, in 1948, has been sent away for additional training.

We have deliberately avoided making distinction between technical and administrative people. Everyone, from the senior people to the young engineer, is required to familiarize himself with and do work in the technical aspects of the job. In a field as novel as nuclear power we cannot permit technical decisions to be made by men who are purely administrators.

It was also necessary in a project of this type to establish an uncompromising standard of excellence. Attention to detail became the rule, because no matter how trivial an item appeared to be, if it might cause trouble, it was, by definition, not a detail.

We assign people to positions on the basis of their managerial and technical capabilities rather than their age or seniority. A man's rank, or whether he is an officer or a civilian, has no bearing on his assignment to a job; his brain and his ability are the only considerations by which he is judged and by which he survives.

From the outset the project has been run as an industrial endeavor, and not as a military operation.

Based on the successful operation of the *Nautilus*, Congress has authorized the Navy to construct six additional nuclear powered submarines. These are in addition to the *Seawolf* which should be in operation in 1956. Four of these will be smaller than the *Nautilus* and *Seawolf*. Preparations to build one of them is going on at the Mare Island Naval Shipyard, here in California. Another has already been started at the Electric Boat Division of General Dynamics Corporation in Groton, Conn., and the other two will be built at the Portsmouth (New Hampshire) Naval Shipyard. One of the remaining two nuclear powered submarines will be a new attack type with a speed even greater than that of the *Nautilus*. The other will be our largest submarine, and the first one to be powered by two reactors. It is being designed to be fast enough to operate in conjunction with a fast carrier task force and to provide it with radar information.

We are also designing nuclear powered surface vessels. The Newport News (Virginia) Shipbuilding and Dry Dock Company has been working for several years on the design of a nuclear powered aircraft carrier. The shipbuilding Division of the Bethlehem Steel Company at Quincy, Massachusetts, has started work on the design of another type of nuclear surface vessel.

Because nuclear power offers tremendous advantages for all naval vessels, there is a demand for a variety of plants. I am pleased to say that the Atomic Energy Commission is developing for the Navy a group of nuclear power plants in a range of power ratings covering all feasible applications. This group consists of a series of reactors ranging from about 3,000 to 40,000 shaft horsepower, which can be used singly or in multiple. Five new types of nuclear power plants are currently being designed for specific ship application.

To illustrate the magnitude of what the Navy plans to do and the speed with which changes are projected, I would like to compare the expected build-up of nuclear powered vessels with the conversion of ships from sail to steam.

Our first naval vessel to be propelled by steam was the *Demologus*, designed and built by Robert Fulton in 1814. For the next twenty years only one additional small vessel was powered by steam, but during this same twenty-year period some 700 commercial American steam vessels were built.

It was many years after the *Demologus* that the Navy stopped constructing the last sailing vessel. In comparison, I predict that by the early 1960's all major naval vessels authorized for construction will be propelled by nuclear power.

What it will take to accomplish this task can be better understood when it is noted that, although the *Nautilus* has more than lived up to our expectations, her atomic power plant represents the beginning in design.

Major advances in many areas are necessary. These include: the development of new uranium alloys for use in reactor cores; greater understanding of reactor physics, of heat transfer, and of the effects of radiation on materials; development of new and im-

proved components such as valves, pumps, heat exchangers, and instruments to meet the new and severe requirments.

In order to accomplish all of this, we must exploit the lessons learned and the new concepts worked out in the course of developing the *Nautilus* and the *Seawolf*.

Let me discuss some of these. We found that the ordinary methods of science, engineering, and production were not entirely adequate for our rigid requirements. Materials which we needed were not available so we had to use available materials under new conditions. Since we could not predict the performance of these materials from previous experience, and because basic components of the reactor plant such as pumps, valves, and instruments could not be ordered from stock, we were forced to undertake large-scale and extensive development and testing programs. Technical information which one might expect to find in handbooks was lacking; and that which did exist was sometimes incorrect. In short, we had to start nearly from scratch and develop new areas in metallurgy and in physics, as well as a virtually new branch of heat transfer and hydraulics. For this we needed new approaches by scientists, by engineers, and by administrators in industry and in government. Even the welders, pipe fitters, machinists, and other skilled workmen all found that conventional standards and practices were not adequate for this new job.

The development of nuclear powered vessels will inevitably generate radical changes in shipbuilding, in construction techniques, and in machinery plant design. The shipbuilder is faced with an entirely new order of structural and arrangement problems because in a nuclear powered ship the reactor must be completely integrated with the hull, just as the engine and the frame of a fighting plane must be designed together.

I have outlined the promises and the problems of nuclear power for the Navy. The performance of the *Nautilus* has made obvious the need for other technical advances to match the capabilities of her revolutionary power plant. The need for better sonar and radar equipment, for better torpedoes and missiles, for better hulls, and for better propellers has now become plain. A whole new vista of technical requirements is emerging. Just as the invention of the automobile opened up a need for a host of new industries, such as petroleum, glass, rubber, and highway construction, so does the *Nautilus* signify the start of many new technological advances in the Navy and, thus, inevitably, throughout industry.

I have tried to be objective in what I have said today. However, it is impossible for one who has been so closely connected with nuclear power, and for so long a time as I have been, to achieve a completely detached viewpoint. So, it is only fair to mention that my remarks may have been colored by the favorable light one tends to cast on his own work.

Leonardo da Vinci, the Florentine renaissance inventor and artist, developed plans for an underwater warship but kept them secret. He was afraid it would make war even more frightful than it already was.

"ENGINEERING"

POWER REACTOR PROJECTS THROUGHOUT THE WORLD

A COMPARATIVE SURVEY OF SCHEMES DESCRIBED AT GENEVA

ACKNOWLEDGEMENT

This article, published in the 7 October 1955 issue of "Engineering," was written by G. W. K. Ford, of the Engineering Research and Development Division, Atomic Energy Research Establishment, Hartwell.

POWER NEEDS AND FUEL SUPPLIES

THE OBJECT of this article is to make a comparative review of the leading engineering characteristics of the power reactor proposals, both in being and planned, which were presented at the Geneva Conference. A few schemes which were not described in detail at the Conference have been referred to and included in the tables because of their comparative or historic interest.

An attempt has been made to bring out, in addition, their relative economics since this is a matter of considerable significance, but it is important to realize the limitations of such comparisons. First, it should be appreciated that the current reactor programs of the only five countries at present engaged in nuclear power production enterprises have rather different motivations and objectives.

Britain faces an imminent rise in fuel costs because coal production is almost static with ever-increasing prices, and fuel imports are necessarily dear. Therefore there is an economic incentive to build nuclear power plants immediately, and this is indeed being undertaken. The cost of power from these early plants is expected to be of the same order as that from coal-burning stations because of the relatively high price of coal in Britain, and they should thus become valuable additions to the existing power sources. It is generally considered that the rising costs of fossil fuels coupled with the usual fall in capital cost to be expected in new types of engineering enterprise will quite rapidly make the nuclear stations competitive. The complicated economics underlying the selling price of the plutonium by-product also considerably affect the economics of these natural-uranium burning power stations.

The United States do not have the same immediate need for domestic nuclear power production, although they clearly recognize that in a few decades they, too, will require nuclear power to keep pace with the increasing population, the rising use of power per head of population, and the depletion and consequent eventual rising cost of fossil fuel reserves. This breathing-space they intend to use for large-scale experiments in nuclear power production technology.

In spite of the fact that the United States is nominally only engaged upon a power demonstration program of an experimental nature, if all the schemes now in the planning stage are implemented the United States will have, by 1965, two or three times the total nuclear power capacity of the United Kingdom. This would not, of course, represent such a large fraction of the total capacity as will have been achieved in Britain by that date.

It is this deliberate intention to carry out a widely varied and very large-scale nuclear power experimental program which led to the presentation of so many papers and the display of such a diversity of advanced nuclear engineering techniques by the

United States at Geneva. It is to be recognized, of course, that an important contribution to this state of affairs has been made by the developments leading up to military applications such as the *Nautilus* and *Sea Wolf* power plants and the aircraft propulsion programs.

The U.S.S.R. nuclear power requirements would appear to be somewhere between those of America and of Britain. The experimental power reactor described is not claimed to be an economic proposition, but it seems that the U.S.S.R. is now proceeding with a nuclear power station construction plan. France is now experimenting with nuclear power production, but her nuclear power needs do not seem to be as pressing as those of Britain and the U.S.S.R.

Canada is about to enter a period when hydro-electric power will no longer suffice, particularly in certain industrialised areas, and foresees a real demand for nuclear power, probably earlier than that forecast for the United States.

CAPITAL AND DEVELOPMENT COSTS

Besides these direct effects of power needs upon the power reactor programs, the following indirect effects and additional considerations must be taken into account when making comparisons.

(a) Some of the plants are definitely experimental in their objectives, although of full-scale power-plant size, and often include large capital charges appropriate to their experimental nature, e.g., the containment buildings for the pressurized-water reactor (PWR) at Shippingport, which may well turn out to be merely a high insurance premium peculiar to an experimental plant; and large development costs may often be hidden in the capital costs tabulated, e.g., 45 million dols. development cost for the PWR.

(b) Capital costs may be very different in different countries and be assessed in different ways, and interest and depreciation rates assumed may differ considerably. Since the cost of power delivered may be made up of roughly two thirds capital charges (c.f. one third for thermal stations) this is clearly a very important factor.

(c) The costs of natural and enriched uranium will vary from country to country. The costs shown in Table I for American reactors assume pure fissile material to cost 30 dols. per gram. The British power costs assume plutonium sold at 33 dols. per gm. (P390) and natural uranium to cost 55 dols. per kg.

TABLE I—*Comparison of Costs*

No. in main table (Table II)	Power electric (MW)	Cost per kW inst. (dols.)	Interest on capital (per cent.)	Power cost, mills per kW hr., 80 per cent. load factor			
				Fixed charges (mills)	Fuel charges (mills)	Operation charges (mills)	Total (mills)
2 (CEANP) ...	75	340	6.6	3.7	4.4	0.7	8.8
– (RAPS(F)) ...	100	–	–	–	–	–	~25
6 (HGPWR) ...	223	–	–	–	–	–	<7.0
9 (APPR) ...	1.0	–	–	27.8	*	25.5	53.3§
13 (D_2PWR) ...	200	200	7.5	3.0	0.5	0.5	4.0
		to 300	7.5	to 7.5	to 1.5	to 1.4	to 10.4
18 (BER III) ...	3.5	–	15	5.9	20.12	8.6	34.6
19 (EBWR) ...	4.5	890	15	19.1	6.6	8.5	34.2
	9.0	445	15	11.4	6.2	4.2	21.8
21 (D_2BWR) ...	248	–	12.0	4.2	2.6†	0.9	7.7
21 (D_2BWR) ...	62	–	12.0	7.7	4.6	2.3	14.6
21 (D_2BWR) ...	62	–	12.0	7.7	5.3	2.3	15.3
(H_2BWR) ...	62.5	–	12.0	6.8	8.6	2.3	17.7
(H_2BWR) ...	61	–	12.0	7.2	5.2	2.3	16.8
	75	300	15	6.5	3.2	2.0	11.5
24 (SGR) ...	100	265	15	5.5	2.5	1.5	9.5
	125	<200	15	4.0	2.0	1.0	7.0
25 (LMFR) ...	210	238	16	5.4	1.7	6.7	7.8
27 (Fast) ...	150	300	10	4.28	2.81	1.0	8.09

NOTES ON TABLE I

CEANP = Central Electricity Authority Nuclear Power Stations.
RAPS(F) = Russian Atomic Power Stations (Future).
HGPWR = Hanford Graphite-Moderated Pressurized-Water Reactor (U.S.A.)
APPR = Army Packaged Power Reactor (U.S.A.)
D_2PWR = Heavy-Water Moderated Pressurized-Water Reactor (Canada).
BER III = Boiling (light water) Experimental Reactor III (U.S.A.).
EBWR = Engine Cold Boiling (light) Water Reactor (U.S.A.).
D_2 BWR = Heavy-Water Moderated Boiling-Water Reactor (U.S.A.).
H_2 BWR = Light-Water Moderated Boiling-Water Reactor (U.S.A.).
SGR = Sodium Graphite Reactor (U.S.A.).
LMFR = Liquid-Metal Fuel Reactor (U-Bi) (U.S.A.)
Fast = Fast Fission Breeder Reactor (U.S.A.).
* = Fuel charges included in fixed and operation charges.
† = Includes all D_2O charges.
§ = For 60 per cent. load factor.

compared with usually assumed costs of 40 dols. per kg. in U.S.A. and 44 dols. per kg. in Canada. Many of the American papers presented also show the effect upon power costs of the lower price of 15 dols. per gm. of fissile material. These cases have been excluded from this review, although this order of price is expected to be attained eventually in both Britain and the U.S.

The reactor schemes described in detail during the Conference sessions did not contain all the active nuclear power proposals in existence. Propulsion units were not discussed at all, nor the package reactor propositions. Nevertheless, package reactors may become in commercial demand in some areas of the world, and the American full-scale nuclear engineering experiments completed to date do in fact fall within the region of the package reactor power requirements, i.e., the 1 to 10 MW (electric) region. The APPR (Army Package Power Reactor) is included in Table II (item 9) for comparison.

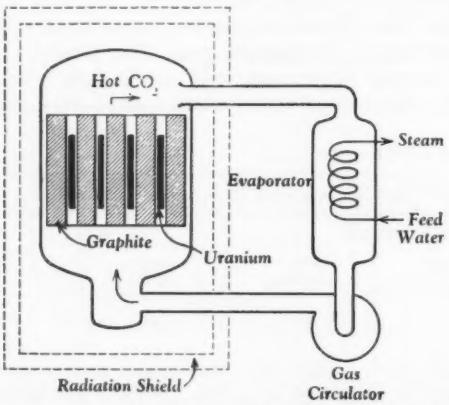


Figure 1. Scheme for Calder Hall station. It is a thermal reactor using natural uranium fuel.

Propulsion units do not, at present, appear to be commercially attractive even for ships. Aircraft propulsion is only of military interest at the moment, and the railway locomotive looks to be an unlikely application on both economic and safety grounds. The *Nautilus* power plant has been included in the table (item 7), however, because it constitutes a notable historic and technological landmark in nuclear power production, though quite uncompetitive as a commercial ship propulsion unit as built.

THREE MAIN CLASSES OF REACTOR

Technically, the reactors described fall into three main classes as follow. (A) Gas-cooled. (B) Water-cooled, including (i) non-boiling pressurized water, and (ii) boiling water. Schemes discussed in both classes (i) and (ii) employ either heavy water (D_2O) or light water (H_2O), and include both heterogeneous (solid fuel elements only in types described) and homogenous (aqueous solution or suspension) examples. (C) Liquid-metal cooled, using (i) liquid metal as coolant only (usually sodium); (ii) liquid metal as fuel and heat carrier. There are also some interesting Netherlands proposals (class D) for using dry fuel powder as a circulating fuel and heat carrier, but these are in the feasibility study stage only.

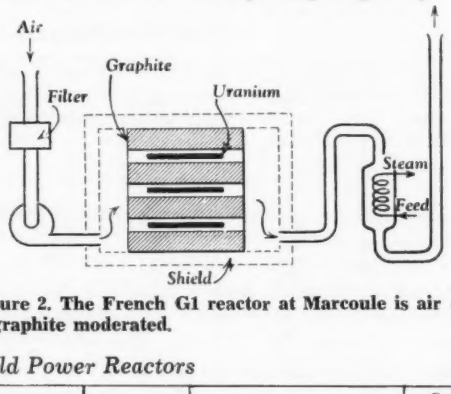


Figure 2. The French G1 reactor at Marcoule is air cooled and graphite moderated.

TABLE II—*A Comparison of World Power Reactors*

No., Fig., Paper Country	Owner, Designer, Location	Name Program, Operating date	Fuel Investment Heat rating	Fertile, Conversion ratio, Product	Moderator, Rating, Temp.	Coolant, Rating, Outlet Temp.	Fuel Can, Heat Flux, Maximum Temp.	Power (MW)		Capital (Million dols.) per kW (dols.) kW hr. (mills.)
								Heat	Elec.	
A.—GAS COOLED REACTORS										
1. (Fig. 1) P406 *(a)* U.K.	U.K. A.E.A. U.K. A.E.A. *(b)* Calder Hall	Calder Hall Plutonium 1956	U nat. (c) — —	U238 — Pu	Graphite — —	CO_2; 105 p — 350 deg. C.	— — 400 deg. C.	— — —	30 per reactor	21 to 28 350 to 555 7 *(d)*
2. (Fig. 1) P390 *(a)* U.K.	C.E.A. Industry —	CEANP Power *(b)*	U nat. 125 tonnes ~2.5 kW per kg.	U238 — Pu	Graphite — —	CO_2 or H_2 — —	— — —	— — —	75 per reactor	27 350 7
3. (Fig. 2) P333 France	— — Marcoule	G1 *(a)* Plutonium 1956	U nat. 100 tonnes 0.4 kW per kg.	U238 — Pu	Graphite — —	Air (At.) — 220 deg. C.	Mg — —	40 — —	5.75 gross *(b)*	— — —
4. (Fig. 3) P337 France	— — Marcoule	G2 Plutonium 1957	U nat. 100 tonnes ~1.2 kW per kg.	U238 — Pu	Graphite — —	CO_2 — 300 deg. C.	Mg *(a)* 400 deg. C.	— — —	30 — —	— — —

NOTES ON TABLE II

Column headings, explanation:

Col. 1. Papers presented at the Geneva conference were given reference numbers, for example P 406; they are to be published in book form next year.

Col. 3. The following letter names for reactors have been used in these tables for cases where no recognized letter name exists:

CEANP = Central Electricity Authority Nuclear Power stations.
RAPS = Russian Atomic Power Station.
RAPS(F) = Russian Atomic Power Stations (Future).
HGPWR = Hanford Graphite Pressurized - Water Reactor.
H_2OPWR = Light-Water Moderated (H_2O) Pressurized-Water-Reactor.
D_2OPWR = Heavy - Water Moderated (D_2O) Pressurized-Water Reactor.
H_2OBWR = Light-Water Moderated (H_2O) Boiling-Water Reactor.
D_2OBWR = Heavy - Water Moderated (D_2O) Boiling Water Reactor.

Col. 4. Fuel: U nat.=Natural uranium (0.725 per cent. uranium 235).

U, x per cent. 235 means x per cent. uranium 235, remainder uranium 238.

U nat + 235 means mixed fuel elements, some natural uranium, some of pure uranium 235.

Investment: Total investment in core of natural or low enrichment uranium given in tonnes or tons, as quoted in paper. 1 tonne=1,000 kg. 1 ton=1,018 kg.

Total investment in core of highly enriched uranium (e.g., 90 per cent.) or pure fissile material given in kg.

In case of highly enriched uranium this usually refers to uranium 235 content only.

Heat rating: For natural or low enrichment uranium heat-rating is given in kilowatts per kilogram (1 kilogram of natural uranium costs 40 dols.)

For pure fissile material heat rating is given in kilowatts per gram (1 gram fissile materials cost 30 dols.)

Col. 5. Fertile: Two possible fertile materials, uranium 238 which converts to plutonium, and thorium which converts to uranium 233.

Conversion ratio: Number of atoms of product fissile material formed by transformation of fertile material for each original fissile atom burned.

Col. 6. Moderators: H_2O=water, D_2O=deuterium oxide=heavy water.

Rating: This figure is of economic interest in heavy-water moderated reactors. Usually figures given refer to entire investment of D_2O in whole system (core plus external circuit). Given as kilowatts per kilogram. D_2O costs 60 dols to 90 dols. per kg.

Col. 7. Coolant: Figure following coolant type is working pressure in lb. per square inch.

Rating: This figure is of technical interest in pressurized-water and boiling-water reactors, referring to the heat extraction rate attainment. In this table it refers to power density in whole liquid contents of core of light-water moderated reactors, to coolant tube contents only of heavy-water moderated reactors (because bulk of moderator in this case must be kept cool if practicable).

Outlet temp: Outlet temperature of coolant.

Col. 8. Heat Flux: usually refers to average heat flux at fuel-can surface for whole core.

Max. Temp.: Maximum can temperature attained in reactor.

Col. 10. Capital: Usually this is the cost (in millions of U.S. dols.) of the entire plant (per reactor) including cost of electricity generation plant.

Per kW (dols.): Cost in dollars of each kilowatt of plant capacity.

kWhr. (mill): Cost (1 mill=0.001 dol.) per kilowatt hour delivered.

Additional information concerning the reactors as numbered:

1. *(a)* Data also taken from "Nuclear Reactors and Power Production," by Sir Christopher Hinton (James Clayton lecture to Institution of Mechanical Engineers, February 26, 1954), and "A programme for Nuclear Power," H.M.S.O., Cmd. 9389.

(b) These reactors are primarily intended as plutonium producers, generating electric power as a by-product. Eight such are to be built: 4 at Calder Hall (two now building), plus 4 at Annan, Dumfriesshire.

(c) Natural or slightly enriched uranium fuel.

(d) The first reactor will produce electricity at 0.76*d*. per unit (=9 mills.). If plutonium by-product is credited, this becomes 0.6*d*. per unit (=7 mill). Natural uranium cost assumed £20,000 per tonne (=56 dols. per kilogram).

2. *(a)* Information also from P. 406 and refs. in note 1*(a)*.

(b) The reactors for the C.E.A. nuclear power stations will be primarily electricity producers, with plutonium as a by-product. Each station will have two reactors. Construction of two stations expected to start mid 1957. Two more will be started 1958-59.

3. *(a)* G1 is a plutonium producer,

(Continued on page 29)

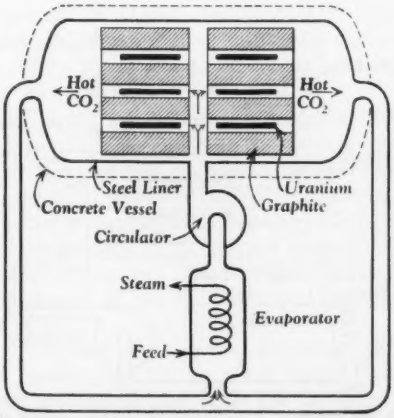


Figure 3. The carbon-dioxide cooled G2 reactor has a split pile with horizontal fuel channels.

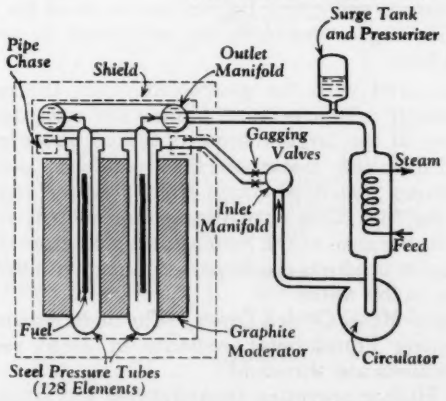


Figure 4. Russian power station. In this system pressurized water serves as coolant and graphite as moderator.

Gas-Cooled Reactors.—Only Britain and France are engaged upon substantial gas-cooled power reactor programs and only a limited amount of technical detail concerning design and performance has been made available. Gas-cooled reactors of the types described have the advantages of inherent nuclear stability in event of accidental coolant loss and negligible chemical reactivity between coolant and fuel during any ensuing overheating; the ability to operate on natural uranium; and quite high coolant outlet temperatures. They share with pressurized water the need for a considerable pressure-vessel container, in the case of the Calder Hall reactors determined by the limit of site-welding practicability (2 in. plate). A sizeable fraction of their gross output must be diverted to coolant circulation. The important fact is that the United Kingdom Atomic Energy Authority have shown that reactors of this type can now be built to be competitive with coal-burning stations as operated in this country.

Water-Cooled Reactors.—These fall into two main classes, non-boiling and boiling. Most of the design studies, and practical proposals to date, which have been submitted to the Conference, fall into the non-boiling or pressurized water category. The main reasons for this are twofold. First, before the Argonne laboratory experiments it was generally considered that boiling within the reactor core would lead to unacceptable nuclear instability, and secondly that the attainable heat extraction rates with natural circulation boiling are lower than those attainable with pressurized water and forced circulation, being limited by the free water surface available for the escape of the steam. This is altered considerably by forced circulation through the boiling region, but this introduces other complications. The main disadvantages of either type are the need for pressure-vessel containment of the reactor core and the low steam temperatures available to the power plant. As will be seen from Table II, the types examined by designers range from natural uranium to pure fissile material for fuel, include heterogeneous (all solid fuel elements) and homogeneous (liquid fuel) arrangements and employ light water, heavy water or graphite for moderators, and either light or heavy water for coolant. Their pros and cons are examined in greater detail later.

Compared with the gas-cooled types, the consequences of pressure-vessel failure are more serious because of the large volume of active water which would flash into steam and later condense, possibly containing fission products from a water reaction with the fuel. This is, of course, enormously multiplied in the case of the homogeneous reactors where the fission products are dispersed, along with the fuel solute, in the water.

Liquid-Metal Cooled Types.—The main reasons for employing liquid-metal coolants in some reactor propositions are threefold.

(a) Higher operating temperatures are attainable than with water, while excellent heat-transfer properties are retained.

(b) Usable liquid metals have low vapor pressures so that no high-pressure containment is required.

(c) For fast fission reactors, gases are out of the question because of the fundamental compactness and consequently extremely high volumetric and surface heat ratings of reactors of this class, and water cannot be used because it softens the neutron spectrum on account of its moderating action upon the emitted neutrons.

SODIUM AND BISMUTH AS COOLANTS

For a variety of reasons, largely connected with neutron absorption or corrosion difficulties, or both, only two liquid metals have emerged which are of serious interest as reactor coolants, namely, sodium and bismuth. Sodium is satisfactorily contained in stainless steel or zirconium and has the additional bonus of being able to be pumped with fair efficiency by the electromagnetic pump. Bismuth has the special property of being able to dissolve sufficient fissile material to make possible a thermal neutron reactor the fuel of which is a pure liquid. It has not proved to be of special interest as a simple coolant in competition with sodium because of its high density, necessitating larger pumping powers and higher pressure differences, its relatively high melting point (271 deg. C. compared with 97 deg. C for sodium) and its high cost. It is also more corrosive than sodium and the containment problem has not yet been completely solved. Therefore, apart from the solution reactor proposal (LMFR) all the liquid-metal cooled power reactors use sodium cooling. The low melting-point sodium-potassium alloy (NaK) is unsuitable for economic reactors because of the high neutron loss to the potassium.

Sodium used to cool a reactor becomes highly radioactive in use, and therefore all the primary circuits have to be shielded to protect the operating personnel. Because of this contained radioactivity and also its chemical reactivity, in particular its ability to burn in air and react with water, and the likelihood of widespread dispersion of its products of combustion (sodium peroxide dust), sodium presents a considerable potential radioactive hazard in event of a serious re-

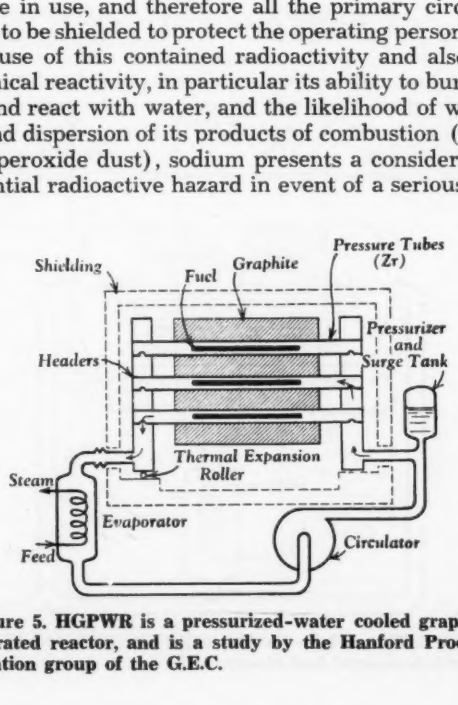


Figure 5. HGPWR is a pressurized-water cooled graphite-moderated reactor, and is a study by the Hanford Products Operation group of the G.E.C.

actor accident, althought fortunately it does not react chemically with the fuel. Therefore, as with water-cooled reactors, the policy in Britain and the United States is either to build such reactors at remote sites or to contain any possible accident product by housing the reactor in a gas-tight vessel, or both. It is interesting to note that the U.S.S.R. pressurized-water reactor is not so contained.

The accident hazard with the LMFR reactor is somewhat different. Although bismuth will burn in air, it is not so chemically reactive as sodium. However, when used as a fuel carrier it contains the fission products either in solution or suspension, or as gases, their concentration depending upon the rate of extraction in the continuous chemical processing system. Therefore there is a formidable safety problem with reactors of this type analogous to those of the water-solution reactors.

GAS-COOLED REACTORS

Having broadly reviewed the main types as distinguished by their coolants, and as further classification becomes increasingly difficult because of the wide variety of designs within each class, it is best now to consider the reactors listed in Table I in turn. Because by far the majority of papers giving economic assessments were from the U.S. all costs are quoted in dollars or mills. One dollar is approximately equivalent to £0.36, and one mill is one tenth of a cent or about 0.9*d*. The letters and figures give the table references.

1. *The Calder Hall Reactors.*—The description of these reactors submitted to the Conference was mainly devoted to the numerous novel mechanical engineering problems which have been ingenously and successfully solved during their design and construction. The most notable feature is the large size of the reactor pressure vessel; it is 40 ft. in diameter and 60 ft. high, is made of 2 in. steel plate and operates at about 100 lb. per square inch internal pressure. The method of supporting the 1,000 tons cylinder of graphite so as to accommodate the differences in thermal expansion of the steel support and the graphite is of considerable interest. No details of the fuel elements were given. The economics are based on a fuel burn-up of 3,000 megawatt-days per tonne (MWd/tonne), but even assuming no sale value for the plutonium by-product, the cost of power sent out is as low as 9 mills per kilowatt-hour.

2. *The C.E.A. Power Station Reactors.*—No details of these reactors were given beyond an indication that their general design would be developed from the Calder Hall reactors and that their economics are expected to be better. The interesting possibility of using hydrogen as a coolant instead of carbon dioxide was mentioned. This would reduce the present pumping power of several thousand horsepower by a factor of 10.

3. *The French Plutonium Producer G1.*—The electric power generation plant being installed at Marcoule in association with G1 is only a power recovery system, since the gross power generated (5.75 MW) is scarcely more than the air circulator power (about 5.6 MW). The primary object of the power plant is to provide an engineering exercise upon which to base full-scale nuclear power plant design. The cooling air is at approximately atmospheric pressure and leaves the reactor at the relatively cool temperature of 220 deg. C.

4. *The French Power Reactor G2.*—This reactor has been designed from the outset as a combined plutonium producer and electricity generator. It is of considerable interest in comparison with the Calder Hall units, being of similar power capacity. There are two major differences. First, the fuel channels are arranged horizontally in G2, and secondly the pile is split into two halves, the coolant being introduced into the center and exhausted at the two ends of the reactor. Another remarkable difference is the employment of a pre-stressed concrete pressure vessel, lined

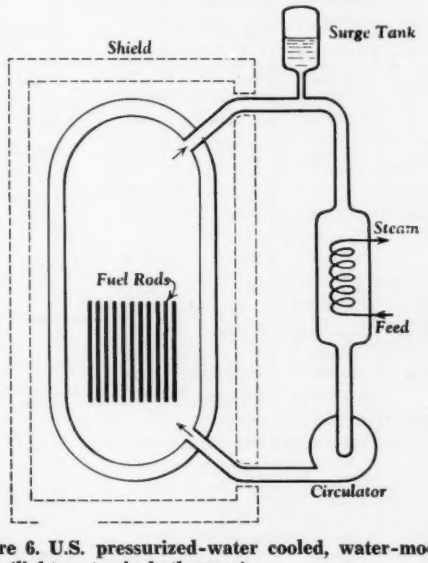


Figure 6. U.S. pressurized-water cooled, water-moderated system (light water in both cases).

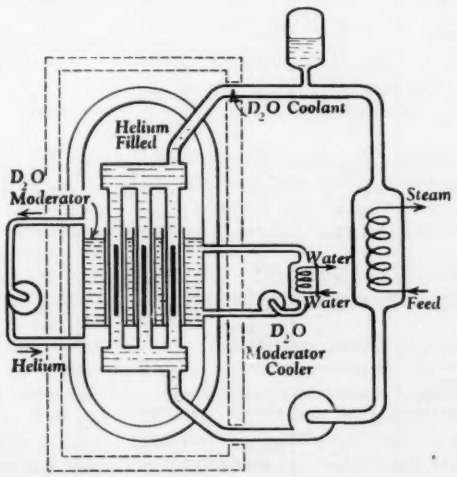


Figure 7. Canadian NPD reactor. This system is moderated and cooled by heavy water.

TABLE II—*Continued*

No., Fig., Paper Country	Owner, Designer, Location	Name Program, Operating date	Fuel Investment Heat rating	Fertile, Conversion ratio, Product	Moderator, Rating, Temp.	Coolant, Rating, Outlet Temp.	Fuel Can, Heat Flux, Maximum Temp.	Power (MW)		Capital (Million dols.) per kW (dols.) kW hr. (mills.)
								Heat	Elec.	
B. WATER-COOLED (i), NON-BOILING REACTORS										
5. (Fig. 4)	—	RAPS	U, 5 per cent. 235	U238	Graphite	H_2O; 1,500 p.	Stainless steel	30	5	—
P615	—	Power	*(a)*	0.32	—	—	*(b)*	—	*(c)*	—
U.S.S.R.	Moscow	June 27, 1954	—	Pu	600 deg. C.	270 deg. C.	175 W per sq. cm.	—	—	*(d)*
6. (Fig. 5)	—	HGPWR	U, 0.92 per cent. 235	U238	Graphite	H_2O; 1,860 p	Zr alloy	800	223	65
P492	Hanford	Study	45 tons *(a)*	—	*(b)*	—	*(c)*	—	—	289
U.S.A.	—	None	17.8 kW per kg.	—	—	310 deg. C.	—	—	—	< 7.0
7. (Fig. 6)	U.S. Gov.	STR-1 and 2	U235 *(b)*	None	H_2O	H_2O	Zr	—	—	—
(a)	Westing-house	Nautilus	—	—	—	—	—	—	—	—
U.S.A.	Idaho	May 31, 1953	—	—	—	—	—	—	—	—
8. (Fig. 6)	U.S. Gov.	PWR	U nat. + 235	U238	H_2O	H_2O; 2,000 p	Zircalloy 2	200	60	85
P815	A.E.C. & W *(a)*	P. Dem.	12 t. + 52 kg. *(b)*	0.8	—	70 kW per ltr.	75 w. per cm.	to *(e)*	to *(f)*	~ 1,000
U.S.A.	Shipping-port	1957	10 K/K, 1.5 K per gm.	Pu	285 deg. C.	285 deg. C. *(c)*	~330 deg. C. *(d)*	340	100	—
9. (Fig. 6)	U.S. Gov.	APPR	U235 *(c)*	None	H_2O	H_2O	Stainless steel	10	1	1.7
(a)	O.R.N.L. *(b)*	Army	25 kg.	—	—	—	—	*(d)*	—	936
U.S.A.	Fort Belvoir	1958	0.4 kW per gm.	—	—	230 deg. C.	—	—	—	53.3
10. (Fig. 6)	Consolidated Edison	H_2OPWR	—	—	H_2O	H_2O	—	500	140	55
—	Babcock	P. Dem. *(a)*	—	—	—	—	—	—	*(b)*	—
U.S.A.	Peckskill	1959	—	—	—	—	—	—	—	—
11. (Fig. 6)	YAE *(b)*	(Yankee)	—	—	H_2O *(e)*	H_2O (e)	—	—	100	20 to 25
(a)	Monsanto *(c)*	PDP	—	—	—	—	—	—	—	—
U.S.A.	Rowe, Mass.	1957 *(d)*	—	—	—	—	—	—	—	—
12. (Fig. 7)	A.E.C.L.	D_2OPWR	U nat.	U238	D_2O	D_2O	Zr	—	20	11
(a)	Can. G.E.	NPD *(c)*	—	—	—	—	—	—	—	550
Canada	Joachims *(b)*	1958	—	Pu	127 deg. C.	260 deg. C.	—	—	—	—
13. (Fig. 7)	—	D_2OPWR	U nat.	U238	D_2O *(d)*	D_2O	Zr	900	200	—
P11	—	Design *(a)*	*(b)*	0.8 *(c)*	—	or	—	*(e)*	—	259 *(f)*
Canada	—	studies	—	Pu	—	H_2O	—	—	—	4 to 10
14. (Fig. 8)	U.S. A.E.C.	HRT-1 *(a)*	U233 or 5	Th *(c)*	D_2O *(d)*	D_2O; ?,000 p	None: Homo-	5 to	2	3
P498	O.R.N.L.	P. Dem.	2.8 kg. *(b)*	1.1 to 1.15	~3 kW per liter	17 kW per liter	geneous reactor	10 —	— —	— —
U.S.A.	Oak Ridge	1956	1.8 kW per gm.	U233	300 deg. C.	300 deg. C.		—	—	—
15. (Fig. 8)	U.S. A.E.C.	HTR	U233 or 5	Th *(b)*	D_2O *(c)*	D_2O; 2,000 p	None: Homo-	440	100	20 to 25
P496	O.R.N.L.	P. Dem.	30 kg. (a)	1.1 to 1.15	36 kW per liter	190 kW per liter	geneous reactor	*(d)*	—	*(e)*
U.S.A.	—	1959	14.6 kW per gm.	U233	300 deg. C.	300 deg. C.	—	—	—	—
16. (Fig. 9)	—	Homo-geneous	U *(a)*	U238	H_2O	H_2O; 750 p	None: Homo-	0.25	Nil	—
P936	—	(Design	—	—	—	—	geneous	—	—	—
Nether-lands	—	study)	—	Pu	—	—	reactor	—	—	—
17. (Fig. 10)	—	PWR/ BWR	U nat.	U238	D_2O *(b)*	D_2O; 400 p	Al alloy	10 *(d)*	2.5	—
P879	—	(Design studies *(a)*	9 tons	—	~1.0 kW per liter	—	*(c)*	15 *(e)*	—	—
Norway	—		1.7 kW per kg.	Pu	60 deg. C. (av.)	230 deg. C.	—	—	—	—

NOTES ON TABLE II—*continued from page 25*

to which a heat recovery plant has been added.

(b) Blower power is about 5.6 MW, so net electric power output is negligible.

4. *(a)* Fuel maximum temperature =550 deg. C.

5. *(a)* 15 per cent. burn-up of uranium 235 is achieved, 20 per cent. by reloading in special fashion.

(b) Pressure tubes through graphite also made of stainless steel.

(c) 50—100 MW (electric) nuclear power stations are now being planned in U.S.S.R.

(d) Power cost said to be comparable with that from 1—5 MW thermal station.

6. *(a)* Fuel could consist of 0.92 per cent. uranium 235 in uranium metal pellets distributed uniformly in a magnesium-alloy matrix to give 65 per cent. uranium metal and 35 per cent. magnesium alloy by volume.

(b) Graphite contained in helium atmosphere.

(c) Fuel elements are 0.9 in. in outside diameter, 0.3 in. in inside diameter; cooled externally.

7. *(a)* A description of this installation, with very few design figures, is given in "Westinghouse Engineer," March and May, 1955.

(b) Fuel is "highly enriched uranium," alloyed with zirconium.

8. *(a)* Joint design by U.S.A.E.C. and Westinghouse. P. Dem.=Power Demonstration Program reactor for U.S.A.E.C.

(b) There are 24 "seed" fuel elements composed of pure ("highly enriched") uranium 235 alloyed with zirconium, and 93 "blanket" fuel elements containing natural uranium-oxide pellets. During initial operation 40 per cent. of output power will come from seed, 60 per cent. from blanket, the latter increasing with time as plutonium is formed. Ratings: seed: 1.54 kW per gm., blanket 10 kW per kg.

(c) The average power densities for whole core contents are: 80 kW per liter in seed zone, 30 kW per liter in blanket zone. Average over whole core is 55 kW per liter. Figure in table is for rating of coolant liquid only in core on assumption fuel elements occupying about one quarter of core volume. Power density (rating) is then directly comparable with boiling reactor coolant ratings quoted.

(d) Saturation temperature for 2,000 lb. per sq. in. water is about 336 deg. C. Metal surface is operated "a few degrees" below this. Average heat flux is 75.5 W per sq. cm., maximum about 120 W per sq. cm.

(e) Sufficient heat will be available from the first core to generate 60 MW electric power. A thermal efficiency of 29.5 per cent. is expected.

(f) Provision is being made to introduce improved cores as development proceeds, thus to bring the total plant output up to 100 MW (electric), the installed capacity of the generator.

9. *(a)* Data from "Power Reactor Package," by Livingston and Block, Oak Ridge National Laboratory (O.-R.N.L.) (Nucleonics, May, 1955).

(b) O.R.N.L. carried out preliminary study. Contract now placed with American Locomotive Company. (O.-R.N.L.=Oak Ridge National Laboratory.)

(c) Fuel "highly enriched uranium."

(d) Power and cost figures refer to O.R.N.L. design study, 60 per cent. load factor. Contract reactor to produce 10 MW heat, 1.7 MW electricity, and contract price is 2.2 million dols.

10. *(a)* Pressurized water reactor for U.S.A.E.C. Power Demonstration Program.

(b) A further 96 MW will be added from oil-fired superheater.

11. *(a)* Not described at Conference.

(b) Y.A.E.=Yankee Atomic Electric Co. PDP=Power Demonstration Proposal (submitted to U.S.A.E.C.).

(c) Monsanto and Fluor Corporations.

(d) If approved to proceed.

(e) Pressurized water, assumed light.

12. *(a)* Data taken from "Atomic Energy in Canada, 1955" issued at Geneva by Atomic Energy of Canada Limited. (A.E.C.L.)

(b) Des Joachims is a village on the Ottawa river about 20 miles from Chalk River.

(c) NPD=Nuclear Power Demonstration.

13. *(a)* This is not a specific reactor design but the conclusions from a general economic study of heavy water natural uranium power system based on considerable experience of high powered research reactors run on heavy water and natural uranium. They are of considerable interest in comparison with the more specific reactor proposals or actual projects listed in the rest of the table.

(b) 3,000 MW days per ton fuel irradiation has been achieved in Canadian piles. 5,000 MW days per ton thought to be a reasonable objective. Complete fuel rods expected to cost 44 dols. per kg.

(c) 0.8 is the conversion ratio assumed in P4 by the same author and assumed to apply to the estimates in P11 quoted.

(d) D_2O assumed to cost 66 dols. to 88 dols. per kg.

(e) Based on 22 per cent. thermal efficiency.

(f) Figures quoted as 200 dols. to 300 dols. per kW installed capacity.

14. *(a)* The Homogeneous Reactor Test (HRT-1) described in P498 is the direct successor to the Homogeneous Reactor Experiment (HRE) which was dismantled early in 1954 after two years of successful experiment.

(b) The nuclear reaction takes place in two physically separated regions, core and blanket. Uranium 235 or uranium 233 solution in heavy water as uranyl sulphate is used in the core, uranium or thorium oxide as a suspension in heavy water is used in the blanket. 2.8 kg. is fissile content of core (= critical mass) only. External hold-up must be accounted.

(c) Thoria suspension in heavy water.

(d) 17 kW per liter of core volume. Mean rating of core plus external circuit hold-up might be a fifth of this (see 15 (c).) In the HRE tests power densities of up to 30 kW per liter of core were attained.

15. *(a)* As in 14 *(b)*; solution of 2.8 gm. fissile uranium per liter heavy water in core.

(b) Suspension of 1,130 gm. thorium (as thorium oxide) per kg. of heavy water (equivalent to 1,000 gm. per liter).

(c) 190 kW per liter of core volume. Mean rating of core plus external circuit hold-up is only 36 kW per liter.

(d) Based on planned nominal electricity output of 100 MW and overall station thermal efficiency of 23 per cent.

(e) This excludes thoria, fissionable material and heavy water inventories. Compares with 15 million dols. for comparable coal-burning power station.

16. *(a)* Intermediate-enriched uranium as oxide suspension in light water.

17. *(a)* Design study started as PWR, later changed to BWR.

(b) Moderator rating of about 1.0 MW per liter D_2O as boiling water reactor. 14 tonnes of D_2O in core, external hold-up not known but assumed small for BWR use.

(Continued on page 32)

with sheet steel to ensure leak-tightness. This pressure vessel is kept cool by circulating cold carbon dioxide gas between the thermal shield and the steel lining. The fuel consists of an alloy of natural uranium and a small quantity of aluminum, each fuel element being sheathed in, and mechanically secured to, a finned magnesium tube. The reactor also has provision for re-charging and discharging fuel whilst the reactor is operating.

WATER-COOLED REACTORS: NON-BOILING

Water-cooled reactors may be divided into (i) non-boiling and (ii) boiling reactors; examples of non-boiling installations will be considered first.

5. *The Russian Atomic Power Station.*—This was the only "dark horse" of the conference. The major details of all the other working or building power reactors described had been known for a considerable time, but nothing whatsoever was known of the RAPS. The most striking fact about the reactor is that it reveals that the U.S.S.R. has an isotope separation plant able to supply considerably enriched uranium for their reactor projects. In the RAPS this enrichment (5 per cent, uranium 235, remainder uranium 238, possibly alloyed to improve fuel-element life) is used to off-set the neutron absorption resulting from the use of stainless-steel cans and coolant channel tubes. As in the Hanford design study (item 6, table II), which, however, employs zirconium coolant tubes, the coolant tubes sustain the full internal pressure of 100 atmospheres and must therefore be relatively thick. No claim is made that this station is an economic proposition, but using the technological experience provided by it the Russian engineers intend to build 100 MW (electric) power stations using two 200 MW (heat) reactors of this type which are expected to be economical. Probably zirconium would eventually replace much of the stainless steel in the commercial designs.

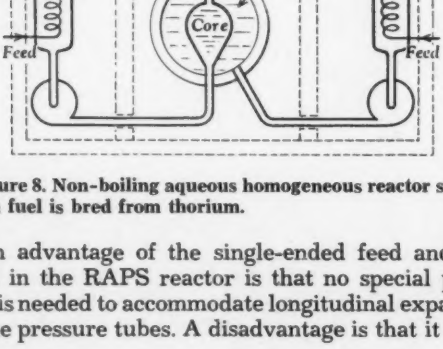


Figure 8. Non-boiling aqueous homogeneous reactor scheme. Fresh fuel is bred from thorium.

An advantage of the single-ended feed and exit used in the RAPS reactor is that no special provision is needed to accommodate longitudinal expansion of the pressure tubes. A disadvantage is that it introduces yet more absorbing material within the reacting core.

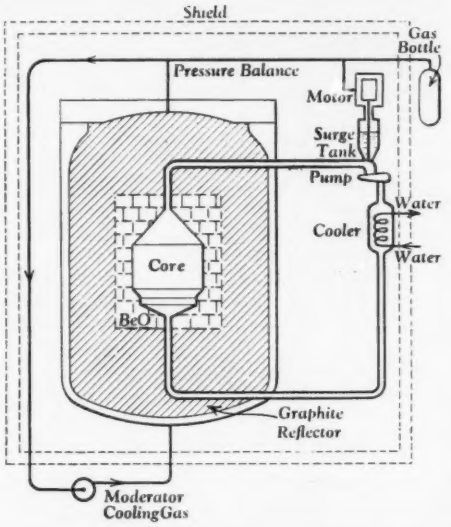


Figure 9. Netherlands homogeneous reactor scheme using light water as both coolant and moderator.

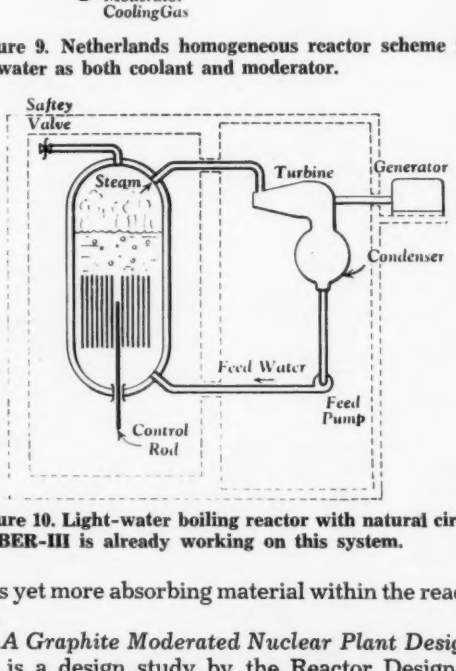


Figure 10. Light-water boiling reactor with natural circulation. BER-III is already working on this system.

6. *A Graphite Moderated Nuclear Plant Design.*—This is a design study by the Reactor Design and Development Unit of the Hanford Products Operation group of the General Electric Company. It is of interest to compare this large 800 MW (heat) reactor proposal with the smaller (200 MW heat) reactors of similar basic type, i.e., water cooled graphite moderated, which the U.S.S.R. intends to build as an extrapolation of the 30 MW (heat) RAPS experience. The Hanford proposal is a natural extrapolation of the 10 years of experience with similar reactors at Hanford itself. The principal differences from the RAPS are that the coolant channels are horizontal, the pressure tubes and fuel cans are of zirconium and, as a consequence, the required enrichment is only 0.92 per cent. uranium 235 (natural uranium contains 0.725 per cent. uranium 235) compared with 2.5 per cent. uranium 235 for the smaller 200 MW (heat)

Russian reactor proposal using stainless-steel pressure tubes and fuel cans. The graphite moderator is kept in an atmosphere of helium, as in the RAPS, which is also used to cool the graphite and to dry it out in event of a pressure-tube failure.

One novelty of this reactor proposal is the gravity operated safety device. Should the normal control-rod system fail, 26 hoppers full of boron-steel balls would be emptied into 26 vertical slots in the graphite. The balls can be restored to their hoppers by means of an electromagnetic conveyer. A further interesting safety measure is the proposal to fit large flywheels to the electric coolant pumps to enable the pumps to be kept running long enough after a main power failure to ensure that the emergency low-power supply needed to keep the pumps running for shut-down cooling (to remove radioactive decay heat, as opposed to fission heat) can be brought into operation.

Because of the danger of flashing all the water into (radioactive) steam in the event of rupture of the primary coolant circuit coupled with the possibility of chemical reaction between molten (radioactive) metals and water, the whole reactor and auxiliaries would be housed within a 225 ft. diameter steel sphere.

Assuming 3,000 MWd per ton fuel burn up, and re-charging one-sixth of the charge on each occasion, the reactor would be shut down for re-charging every 27 days. The minimum shut-down time would then be 38 hours owing to decay-product reactivity poisoning effects. The estimated power cost is less than 0.7 mills per kW hr. which in fact makes this one of the most economic proposals presented.

7, 8, 9, 10 *and* 11. *Pressurized-Water Cooled, Light-Water Moderated Reactors.*—Only one of this class of reactor was described in detail at the conference, namely the Shippingport PWR. The other four reactors, tabulated have been included for reference, since this is an important class of reactor as evidenced by the number in this class either working or under consideration. The first power-producing unit of this class was the land-based version, named STR-1, of the (identical) *Nautilus* power plant, and the same system is to form the basis of the Army Packaged Power Reactor (APPR) and two further Power Demonstration Program reactors proposed by the Consolidated Edison group and the Yankee Atomic Electric group.

The use of light water as moderator necessitates some degree of enrichment of the uranium fuel in the U235 isotope. In the Shippingport reactor this is achieved by using a highly enriched "seed" (24 elements) and a natural uranium oxide "blanket" (93 elements). In order to secure adequate burn-up of the fissile content (initially U235 only, later both U235 and the plutonium formed from the U238) it is necessary to burn at least two seed elements for each blanket element consumed.

It is of interest to note the basic criteria for the thermal design of the PWR, especially in comparison with the boiling reactors discussed later. These are as follows:

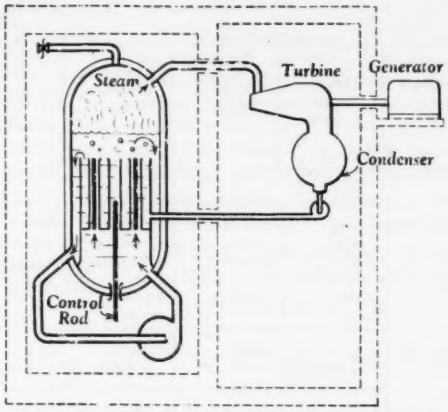


Figure 11. Heavy-water boiling reactor with forced circulation. (U.S. design studios.)

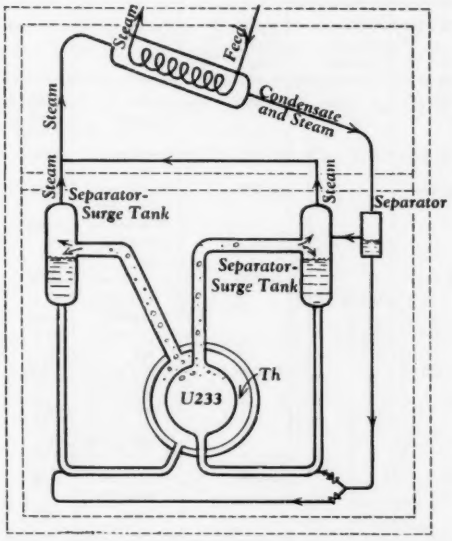


Figure 12. Homogeneous boiling breeder scheme with natural circulation. Fissile uranium 233 is bred from thorium.

(a) Nucleate boiling must not occur at the hot spots during steady operation.

(b) Bulk boiling must not occur in water leaving the hot channel either during steady operation or normal power change transients.

(c) Fuel element internal and surface temperatures must be compatible with the properties of the selected fuel element materials.

These requirements entail keeping the maximum temperatures of the coolant water and of the hottest fuel element surfaces below 335 deg. C., the saturation temperature at 2,000 lb. per square inch. Under these conditions the Zircalloy-2 cladding appears to be very satisfactory as regards corrosion. Even if the cladding fails neither the uranium oxide nor the U235-zirconium alloy reacts with the high temperature water. Also, neither material suffers serious radiation distortion so that high burn-ups are expected.

TABLE II—*Continued*

No., Fig., Paper Country	Owner, Designer, Location	Name Program, Operating date	Fuel Investment Heat rating	Fertile, Conversion ratio, Product	Moderator, Rating, Temp.	Coolant, Rating, Outlet Temp.	Fuel Can, Heat Flux, Maximum Temp.	Power (MW)		Capital (Million dols.) per kW (dols.) kW hr. (mills.)
								Heat	Elec.	
(ii) BOILING REACTORS										
18. (Fig. 10)	U.S. A.E.C.	BER-III *(b)*	U, 90 per cent. 235	Nil *(c)*	H_2O	H_2O; 300 p	Aluminum	15	3.5	0.55*(f)*
P851	A.N.L. *(a)*	Argonne	11.8kg. 235	—	—	35 kW per liter	12.5 W per sq. cm.	—	—	100
U.S.A.	Idaho	Operating	1.3 kW per gm.	—	240 deg. C.	240 deg. C. *(d)*	215 deg. C. *(e)*	—	—	34.6
19. (Fig. 10)	U.S. A.E.C.	EBWR	U nat. + U 235 *(a)*	U238	H_2O *(b)*	H_2O; 600 p	Zircalloy 2	20	5	4
P497	A.N.L.	P. Dem.	4.5 t + 19 kg.	0.7	—	25 kW per liter	12.5 W per sq. cm. *(c)*	—	—	800
U.S.A.	Lemont	1956	2.8 kW per kg.; 0.39 kW per gm.	Pu	252 deg. C	252 deg. C.	265 deg. C.	—	—	21.8*(e)*
20. (Fig. 10)	N.P.G.	H_2BWR	—	—	H_2O	H_2O	—	670	180	—
—	G.E. Co.	PDP *(a)*	—	—	—	—	—	—	—	—
U.S.A.	Chicago	1960	—	—	—	—	—	—	—	—
21. (Fig. 11)	—	D_2BWR	U nat.	U238	D_2O *(d)*	D_2O, 600 p.	Zircalloy—2	1,000	248	—
P495	*(a)*		43.4 tons	0.901 *(c)*	8.3 kW per liter	110 kW per liter	50W per sq. cm.			—
U.S.A.			23 kW per kg.	Pu	90 deg. C.	250 deg. C. *(e)*	(average)			7.7
(Fig. 11)		D_2BWR	U, 0.92 per cent. 235	U238	D_2O	D_2O, 600 p.		250	62	—
			10.8 tons *(b)*	0.869	—	—				—
			18.5 KW per kg.	Pu	90 deg. C.	250 deg. C.				14.6
(Fig. 11)	Design studies	D_2BWR	U, 0.85 per cent. 235	U238	90 per cent. D_2O + 10 per cent. H_2O mixed	600 p.		250	62	—
			10.8 tons	0.766	—	—				—
			18.5 kW per kg.	Pu	90 deg. C.	250 deg. C.				15.3
(Fig. 10)		H_2BWR	U, 1.1 per cent. 235	U238	H_2O	H_2O, 600 p.		250	62.5	—
			72 tons	0.84	—	40 kW per liter				—
			3.5 kW per kg.	Pu	250 deg. C.	250 deg. C. *(f)*				17.7
(g)		H_2BWR	U, 1.15 per cent. 235	U238	H_2O	H_2O, 600 p.		250	61	—
			36 tons	0.82	—	80 kW per liter				—
			7 kW. per kg.	Pu	250 deg. C.	250 deg. C.				16.8
22. (Fig. 12)	—	Homogeneous Boiling	U233 or 5	Th *(c)*	D_2O or H_2O		—	—	—	—
P624	*(a)*		*(b)*	—	3-5 kW per liter	—	—	—	—	—
U.S.S.R.	—	—	1.5-3 KW per gm.	U233	—	—	—	—	—	—

NOTES ON TABLE II—*continued from page 29*

(c) Max. fuel temperature 380 deg. C.

(d) As PWR.

(e) As BWR. Moderator rating quoted would also apply to this case only.

18. *(a)* A.N.L.=Argonne National Laboratory.

(b) This reactor has been operated with two experimental cores. The figures quoted refer to the second core of highest rating.

(c) Not strictly true because of 10 per cent. residual uranium 238.

(d) 20-30 kW per liter average core power density; 30 to 40 kW per liter of water in core.

(e) Average heat flux=12.5 W per sq. cm., maximum about 30 W per sq. cm.

(f) More than half the total cost of the entire plant was in the power conversion equipment and cooling facilities.

19. *(a)* Charge made up of 77 natural uranium fuel elements and 35 uranium 235 assemblies. (85 per cent. to 90 per cent. uranium 235.) Enriched elements contribute 37 per cent. of total heat output.

(b) Provision is made for changing the core to enable operation of heavy water (D_2O) at a later date.

(c) Average heat flux 12.5 W per sq. cm. Maximum at hot spots 44 W per sq. cm. Burn-out about 190 W per sq. cm.

(d) Maximum fuel temperature= 294 deg. C.

(e) Economic assessment assumes 10,000 MW days per tonne radiation of fuel, 40 dols. per kg. natural uranium, 30 dols per gm. uranium 235. For 4.5 MW (electric), power cost 34.2 mills per kW hr. For 9.0 MW

(Continued on page 33)

NOTES ON TABLE II—*continued from page 32*

(electric), power cost 21.8 mills per kW hr. Second cost includes installation of second 5 MW electric set. Average 10 MW coal-burning plant in U.S.A. produces power at between 10 and 12 mills per kW hr.

20. *(a)* PDP = Power Demonstration Proposal submitted to U.S.A.E.C.

21. *(a)* These are design studies only.

(b) In all except first case the core is "spiked" with enriched uranium fuel elements as the fuel burn-up proceeds to preserve reactivity up to 10,000 MW days per ton.

(c) Conversion ratio expected to be sufficiently high to maintain reactor critical for 10,000 MW days per ton fuel irradiation using natural uranium fuel additions only.

(d) First reactor has 100 tons of D_2O in reactor plus 20 tons in external hold-up. At 62 dols. per kg. this contributes 1 mill. kW hr. to the power cost.

(e) Approximately 110 kW per liter of liquid in core flow channels. Main volume of moderator kept at much lower temperature. Average power rating of D_2O core only (excluding reflector) is 26 kW per liter. Average power rating for D_2O in whole system, including external hold-up, is 8.3 kW per liter D_2O.

(f) This uses natural convection of coolant. All other cases assume

(Continued on page 34)

The central temperature in the hot-compacted and sintered uranium oxide blanket pellets may be as high as 1,200 deg. C.; this is still about 1,650 deg. C. below the melting point. It is not stated how a satisfactory thermal bond is made between the oxide pellets and the Zircalloy can (tube), but the pellets are said to be "ground to extreme accuracy" before loading into the tubing. In the plate-type seed elements an efficient metallurgical bond can readily be achieved, probably by hot rolling. The maximum surface heat fluxes are 75 watts per sq. cm. in the blanket, 120 watts per sq. cm. in the seed assemblies.

The temperature of the dry saturated steam supplied to the turbine from the evaporator is about 250 deg. C. at 600 lb. per square inch (depending on load). Using a special regenerative turbine arrangement a thermal efficiency of 29.5 per cent. is attained, compared with 26.5 per cent. for a simple condensing cycle— (both figures refer to 545 lb. per sq. in. gauge).

The whole nuclear portion of the Shippingport plant is to be built within a gas-tight steel containing vessel to meet the present safety requirement policy for this class of reactor.

12 *and* 13. *Canadian Pressurized Heavy-Water Power Reactor Proposals.*—The big difference between these proposals and the other pressurized-water schemes is that the use of heavy water as a moderator enables the fuel to be natural uranium only. The main disadvantage is that the capital investment in heavy water is very high. Nevertheless, the forecasts made in P4 and P11 at the Conference indicate that the cost of power may be fully competitive with the alternative PWR schemes using enriched uranium feed. There are some added engineering difficulties in ensuring very low losses of heavy water from the plant, but the leakage of primary water must in any case be kept very low even in a light-water PWR on account of the induced radioactivity.

An experimental power reactor of this type, named NPD (Nuclear Power Demonstration) is now being designed and is intended to be in service at Des Joachims, on the Ottawa River near Chalk River, in 1958.

14 *and* 15. *Non-Boiling Aqueous Homogeneous Reactor Schemes (HRT1 and HTR).* — Although requiring the solution of numerous difficult technical problems, the two-region non-boiling homogeneous thorium breeder scheme, which has yet to be tested in full-scale operation, appears to offer some remarkable possibilities for the development of really economical nuclear power. The principles underlying the operation of this system are as follows:

(a) The fuel feed to the plant will be natural thorium (which is not a fissionable element), as the oxide, thoria.

(b) This material is circulated outside the reacting core as a suspension of thoria in heavy water. Neutrons leaking out from the core are absorbed by thorium nuclei which are transmuted into protoactinium, which decays radioactively to form the fissile material U233.

(c) Some of the neutrons in the blanket cause

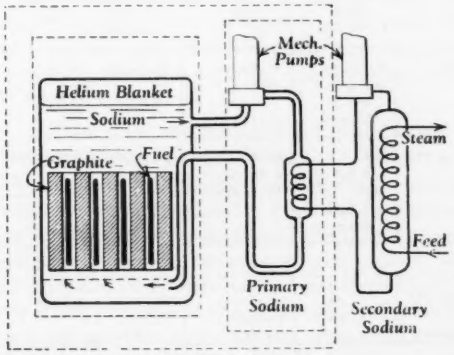


Figure 13. Sodium graphite system; the graphite is carried in zirconium. It would be self-sustaining on thorium and could operate at high temperatures.

fission of the newly-created U233, so that a considerable amount of heat energy is released in the blanket, and also more neutrons to contribute to the two nuclear processes.

(d) The circulating blanket suspension is continuously processed on a by-pass system by centrifuging out the thoria (containing U233) and passing the dried material thus separated from the heavy water to the U233 extraction plant.

(e) The U233 thus obtained is used as fuel for the core in the form of uranyl sulphate (UO_2SO_4) solution.

(f) The core solution is also circulated and processed on a by-pass system so as continuously to remove fission product solids (e.g., by centrifuging) and gases, thus removing the "ashes" of the "burned" U233.

(g) Useful heat is extracted from both circuits as in other PWR reactors.

TABLE II—*Continued*

No., Fig., Paper Country	Owner, Designer, Location	Name Program, Operating date	Fuel Investment Heat rating	Fertile, Conversion ratio, Product	Moderator, Rating, Temp.	Coolant, Rating, Outlet Temp.	Fuel Can, Heat Flux, Maximum Temp.	Power (MW) Heat	Power (MW) Elec.	Capital (Million dols.) per kW (dols.) kW hr. (mills.)
C. LIQUID METAL COOLED REACTORS										
23. (Fig. 13) P499 U.S.A.	U.S. A.E.C. N.A.A. *(a)* S. Susana	SRE *(b)* P. Dem 1956	U, 2.8 per cent. 235 2 to 2.5 t. ~10 kW per kg.	U238 ~0.7 Pu	Graphite *(c)* ~550 deg. C.	Sodium *(d)(e)* 515 deg. C.	Stainless steel *(f)*	20	Nil. *(g)*	4(h) — —
24. (Fig. 13) P493 U.S.A.	C.P.P.D.C. *(a)* N.A.A. Nebraska	SGR PDP *(b)* 1959	U*(c)*: 10.6 kW per kg. U-Th *(d)*: 0.7 kW per gm. 238: 0.7 Pu Th: 0.9 233	Graphite — —	Sodium — 510 deg. C.	Stainless steel — —	250 *(e)* 400	75 100 125	— 300 to 200 11.5 to 7.0
25. (Fig. 14) P493 U.S.A.	— Brookhaven —	LMFR *(a)* Studies *(b)* — —	U233 *(c)* ~170 kg. 3.2 kW per gm.	Th 1.05 U233	Graphite *(d)* —	Bismuth 22 KW per liter *(e)* 550 deg. C.	None — —	550	210	50 238 7.8
26. (Fig. 15) P813 U.S.A.	U.S. A.E.C. A.N.L. *(a)* A.N.L.	EBR *(b)* Argonne December, 1951	U, 90 per cent. 235 52 kg. ~0.03 kW per gm.	U238 1.01 Pu	None *(c)* —	NaK *(d)* — 316 deg. C.	Stainless steel — *(e)*	1.4	~0.2 *(f)*	— — —
27. (Fig. 16) P501 U.S.A.	U.S. A.E.C. A.N.L. Idaho	EBR II *(a)* P. Dem 1958	Pu-U alloy (500 kg./*(b)*) (1.0 kW per gm.)	U238 (1.5) Pu	None —	Sodium 480 deg. C.		60 (500)	20 (150)	(45) (300) (8.09)
28. (Fig. 15) *(a)* U.S.A.	A.P.D.A. A.P.D.A. *(b)* Michigan	F. Breeder PDP *(c)* 58	Pu-U alloy — —	U238 — Pu	None — —	Sodium — —		300	90	29 323 —
29. (Fig. 15) P405 U.K.	U.K. A.E.A. U.K. A.E.A. Dounreay	Fast Breeder Experiment — —	235 or Pu — —	U238 — Pu	None — —	Sodium — —	— — —	60	—	— — —
D. FLUIDIZED SOLID COOLED REACTOR										
30. (Fig. 17) P938 Netherlands	— — —	— Design study	UO_2 nat. 175 t. 1.7 kW per kg.	U238 — Pu	D_2O 3 kW per liter Cool	Fluidized UO_2 1,200 deg. C.	Graphite	300	—	— — —

NOTES ON TABLE II—*continued from page 33*

forced convection.

(g) As Fig. 11, but with close-spaced fuel elements and no special provision for cooling moderator separately.

22. *(a)* These are design studies only.

(b) Uranium in oxide form as aqueous suspension.

(c) Thorium in oxide form as aqueous suspension.

23. *(a)* N.A.A. = North American Aviation Co.

(b) SRE=Sodium Reactor Experiment.

(c) Graphite is canned in zirconium and immersed in sodium for cooling.

(d) All liquid-metal cooled reactors work near to atmospheric pressure.

(e) All main components have been stressed for 650 deg. C. working, a target operation temperature being aimed at during the experimental program.

(f) A film of NaK (sodium potassium low melting point alloy) 0.010 in. average thickness provides heat conduction between the uranium metal surface and the stainless-steel cladding. Maximum uranium temperature=650 deg. C.

(g) Not at present intended to provide a power plant.

(h) This figure does not include development costs, which bring the program to about 10 million dols.

24. *(a)* C.P.P.D.C. = Consumers Public Power District of Columbia.

(b) The SGR proposal has now apparently become one of the four industrial Power Demonstration Proposals (PDP) submitted to the U.S.A.E.C. under which industry would bear 80 to 90 per cent of the costs.

(c) First proposed core has fuel elements of enriched uranium metal 1.8 per cent of uranium 235, initial loading content 443 kg. of uranium 235 (in 24.6 tonnes total uranium). Maximum uranium temperature 650 deg. C. (compare alpha-beta change point 660 deg. C.)

(d) Second proposed core has fuel elements of uranium 235-thorium alloy, 3.70 per cent uranium 235. Maximum metal temperature is 870 deg. C., but this is not a limiting factor. Fuel rating shown in terms of fissile content. Initial fissile investment 360.4 kg. of uranium 235.

(e) The third set of power figures refers to possible future attainments

(Continued on page 35)

NOTES ON TABLE II—*continued from page 34*

using a thorium blanket instead of a graphite reflector, a larger core and improved core design, but retaining temperature limits of first and second cores. The conversion ratio would then be near unity.

25. *(a)* LMFR=Liquid-Metal Fuel Reactor, project of Brookhaven National Laboratory.

(b) Studies only, backed by substantial experimental work.

(c) About 670 parts per million uranium 233 solution in molten bismuth.

(d) Graphite in direct contact with bismuth solution.

(e) 22 kW per liter of bismuth in whole circuit. Cost of bismuth per liter of same order as cost of heavy water per liter. Figure should be compared with moderator ratings of D_2O moderated systems.

26. *(a)* A.N.L.=Argonne National Laboratory.

(b) EBR = Experimental Breeder Reactor. This is essentially a high fast flux fast fission research reactor with a demonstration scale heat recovery plant of about 17 per cent overall thermal efficiency.

(c) Fast fission reactor. No neutron moderation.

(d) NaK is a low melting point alloy of sodium and potassium.

(e) Maximum fuel temperature= 357 deg. C.

(f) Recovery plant only for demonstration.

27. *(a)* EBR II: Experimental Breeder Reactor. One of the five Power Demonstration Program reactors to be built under U.S.A.E.C. sponsorship. Building to commence in 1956.

(b) All figures in parentheses refer to a study of a 500 MW (heat) reactor of the same class to demonstrate the ultimate potentialities of the fast breeder system.

28. *(a)* Data taken from special paper issued by U.S. library at Geneva. Pumps indicated as mechanical.

(b) A.P.D.A.=Atomic Power Development Associates Inc., a group of 25 electric power systems, 4 manufacturing enterprises and 4 engineering organizations.

(c) PDP = power demonstration proposal submitted to U.S.A.E.C.

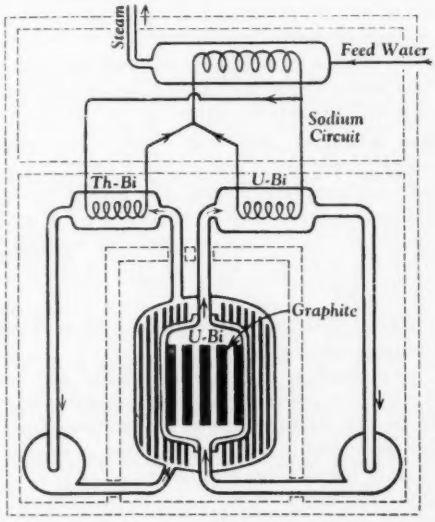


Figure 14. LMFR bismuth-uranium liquid-metal fueled reactor; it has a positive breeding gain.

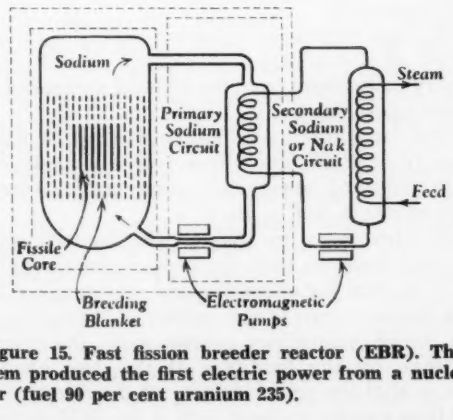


Figure 15. Fast fission breeder reactor (EBR). This U.S. system produced the first electric power from a nuclear reactor (fuel 90 per cent uranium 235).

The operation of this type of reactor appears to be remarkably simple. Because of its large degree of inherent nuclear stability (owing to the very large negative temperature coefficient of reactivity) no mechanical control rods are required. The average temperature of the core is controlled by varying the concentration of fuel, and the power level is governed solely by the rate of heat removal from the core. If the power demand falls, the core temperature rises, the liquid expands and so some fuel solution is removed from the core and stored in the surge tank, thus reducing the core activity; and vice-versa if the power demand rises.

The outstanding advantages of the system as regards economics are as follows:

(a) Because of the absence of absorbing structural materials within the reacting regions (with the exception of the low-cross-section Zircalloy-2 "neutron window" core tank), because of the use of heavy water as moderator with its low neutron absorption cross-section, because of the high value of η (number of neutrons emitted per neutron absorbed in fissile material) for U233, and because neutron-absorbing poisons in the form of fission products can be considerably reduced by the continuous extraction process, there is a very good chance of an overall conversion factor considerably greater than unity for this system so that more U233 will be bred per neutron cycle than is burned by fission. In P496 the authors estimate that the doubling time of this process would be about 1,500 days for item 15.

(b) There is no solid fuel element to set a limit to attainable fuel irradiation time and consequent fractional burn-up of its fissile content (due to either metallurgical failure on account of radiation damage or to loss of reactivity due to depletion of fissile content). In effect, the whole reactor is a single fuel element whose condition is held roughly constant by continuous treatment.

(c) A high power density and low fuel inventory can be achieved. In the P496 proposal an overall fuel rating of 12 kW per gm. of fuel is expected. In the HRT-1 the fuel rating in the core alone is 1.77 kW per gm. of U235. The overall rating in the last case

is less than 1.77 kW per gm. depending upon relative core and external hold-up volumes.

The primary difficulties associated with the system are concerned with the safe handling of the very high levels of radioactivity in the high-pressure, high-temperature circulating systems, and the corrosion problems encountered under the combined conditions of intense irradiation, high temperature and high pressure. There are numerous difficult chemical problems in the extraction systems, particularly on account of the intense radiation emitted by the materials being processed.

16. *The Netherlands Homogeneous Reactor Proposals.*—A fairly detailed scheme was presented for a small-scale experimental reactor using a suspension of enriched uranium in oxide form in light water. This would be used to investigate the properties of this class of system with a view to the ultimate development of a breeder reactor using thorium oxide enriched with U233 as a suspension in heavy water. This would be a one-region circulating fuel homogeneous thorium breeder reactor as defined in the United States paper P496, in which fuel and fertile materials are mixed. In this case it is proposed to surround the core vessel, presumably to be made of zirconium, with a beryllium oxide and graphite reflector, the whole assembly being contained within a gas-filled pressure vessel, the water within the thin-walled core tank being pressurized from the same gas source. No details of the expected economics are given.

The authors of P496 state that following a satisfactory zero-energy experiment, a small-scale enriched reactor will be built.

17. *The Norwegian PWR or Boiling-Water Proposal.*—This heterogeneous water moderated reactor proposal has been taken last under class B (i) because it is a description of a design study which started off as a PWR and eventually developed into a boiling-water reactor, which is the next class to be described.

The design approach was conditioned by the desire to rely upon natural uranium fuel and heavy-water moderator only. This requirement enforces the use of cool moderator, and in this design entails some provision for heat insulation between coolant water and moderator in the form of low cross-section hot-water-proof ceramics. This has proved a difficult thing to obtain, and coupled with the new knowledge that enriched uranium would be available if the reactor, when constructed, failed to go critical at the operating temperature, led to the adoption of a boiling-reactor design. It was found by calculation that the loss of reactivity on account of the hotter moderator was just offset by the gain due to the omission of coolant tubes, so that the original aim of the design may still be preserved. It is of interest in this connection to compare this design with item 21, case 1, for a large D_2O (heavy water) boiling-reactor in which it is also considered necessary to keep the main bulk of moderator D_2O cooler than the coolant (boiling) D_2O.

The final proposition selected for further study is the D_2O boiling reactor with natural uranium metal fuel elements clad in aluminum-alloy tubes, operating at 427 lb. per sq. in. (as compared with 570 lb. per sq. in. for the PWR), 230 deg. C., giving some 10 MW of heat or 2.5 MW electricity for an investment of 14 tonnes (plus external hold up) of D_2O and 8.2 tonnes of uranium. It is to be housed in a rock cavern to contain any explosion.

Proposed applications for plant of this category include small-scale industrial power production, ship propulsion, and process heat for industry. The economics are not analyzed, but it is again of interest to compare with item 21, case 1, in which the heat output is 10 MW per ton of D_2O compared with 0.7 or, at best, 1.4 MW per ton of D_2O in the present proposal.

18. *The First Power-Producing Boiling-Water Reactor, BER-III.*—The description of this reactor given in P851 and of its two non-power producing predecessors, I (named "Borax") and II (which was an experimental core in BER-III pressure vessel), described in P481, has aroused great interest. The termination of the successful series of tests with Borax culminated in a run-away test to destruction affected by means of a spring-ejected control plate, which test went to prove that a reactor of this class is difficult to destroy because of its inherent self-regulation qualities, and that even when self-destroyed explosively does not present anything of the nature of a catastrophe. Practically all the fuel originally in the reactor could be accounted for within a radius of 350 ft., and it was considered that no large fraction of the material left the site in the form of air-borne matter.

The main advantages of the boiling type of reactor may be enumerated as follow.

(a) The reduction of pressure within the reactor vessel for a given pressure and temperature of steam supplied to the turbine, make for either cheapness or larger practicable core sizes, and a lower temperature duty for the fuel elements.

(b) The simplicity of the system is such that the required steam is formed directly within the reactor so that no auxiliary steam-raising equipment is necessary, with consequent saving in pumping power and capital investment.

(c) A high degree of inherent safety and self-limitation of reactivity under fault conditions is demonstrated to result from the effect of steam-bubble formation upon reactivity.

The first two points are brought out in Fig. 18, which is taken from P497, and illustrates the savings of pressure, pumping power and equipment for a steam delivery of 600 lb. per sq. in.

The disadvantages are that (i) the steam is somewhat radioactive, so that the power plant requires special provision for operation and maintenance and (ii) the power output of the reactor is limited by the rate at which steam can escape from the reactor rather than by the heat-flux at the fuel element surface, so that the power density of the reactor may be less than can be attained with a non-boiling pressurized-water cooled core. Power densities of 20 to 30 kilowatts per liter of total core volume were at-

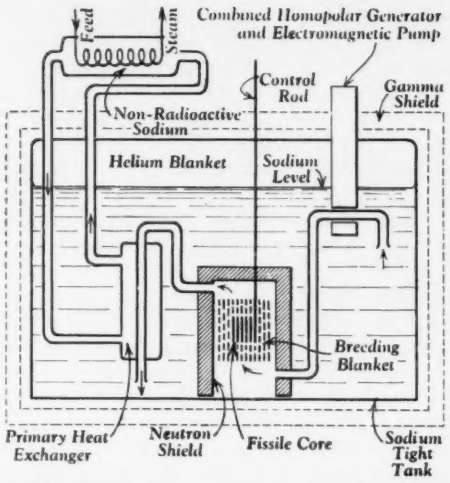


Figure 16. Building of an experimental fast breeder reactor (EBR-II) will commence in the U.S. in 1956.

tained in the BER-III reactor. The average power densities expected from the first Shippingport PWR core are just over 40 kW per liter of core, and it is expected to work this up to the region of 70 kW per liter with improved cores. Nevertheless, it is also possible to improve the power density of boiling reactors. The two likely methods are either the addition of a natural convection chimney over the core, or the use of forced circulation by means of a pump.

With regard to the radioactivity of the steam it is found that because of effective de-trainment of moisture and particulate matter the steam activity is down by a factor 10^4 on the water activity within the reactor. In this connection it should be remembered that in a PWR the primary circuit pumps and heat exchanger (evaporator) must handle the full activity of the reactor core water, although in a more highly rated BWR forced circulation of water within the reactor by means of an external pump circuit may well be needed.

The striking thing about the Borax and BER-III experiments is the boldness of their conception. Those responsible for these ambitious nuclear engineering experiments believe that by building experimental reactors of this type directly, instead of going through the more conservative stages of running loop tests in test reactors and carrying out numerous other auxiliary tests and additional refined calculations, they have obtained more useful results in shorter time with the use of fewer reactor technologists than would otherwise have been possible. They further suggest that this experience strongly suggests this procedure to have application to the investigation of other new reactor types. Indeed, this procedure was followed by the Oak Ridge National Laboratory in their homogeneous reactor program: the HRE (Homogeneous Reactor Experiment), which had no power conversion equipment, was built in 1951 and dismantled for inspection after two years successful running. This is now being followed by a demonstration-size thorium breeder power producing reactor (HRT-1) on very much the same scale as the BER-III.

It is worth calling attention to a significant difference between the control problems in the homogeneous non-boiling reactor and the heterogeneous boiling reactor. In the first type an increase of power demand momentarily cools the reactor and the fuel solution contracts (due to its thermal coefficient of expansion) so that automatically more active solution flows into the core (and circuit) from the surge-tank, thus increasing reactivity and hence automatically increasing heat output to compensate for the changed conditions; and vice-versa. In the boiling reactor an increase in power demand reduces the steam pressure, momentarily, above the core space, thus increasing the steam voidage (relative volume of water occupied by steam bubbles) within the core, thereby increasing the total neutron leakage from the core and so reducing activity; and conversely. Therefore, although essentially a safe system in terms of a run-away, it is inherently an instable system as regards power regulation. Therefore, in the EBWR (item 19 below) it is planned to regulate power demand changes within a 5 per cent. limit by permanently by-passing a nominal 5 per cent. of the reactor output steam past the turbine to the condenser, holding the reactor pressure constant by adjusting this by-pass to suit minor load changes. Large but slow changes of power are dealt with by automatically re-adjusting the reactor power level to maintain this 5 per cent steam by-pass for all loads. Sudden large power changes are dealt with by automatically by-passing up to the full reactor steam output to the turbine condenser after which the reactor power level is reduced by inserting the control rods.

Unlike the homogeneous reactor, the boiling reactor also has a prompt temperature coefficient consequent on the instantaneous expansion of fuel elements with increase of power generation (and therefore of element temperature), and a delayed coefficient due to steam bubble formation. They differ yet again from the PWR types in this respect, which have neither the bubble-formation control or the concentration change effect. A PWR requires a much more carefully regulated control system.

19 *and* 20. *Full-Scale Boiling Reactor Power Plant Demonstrations.*—Two full-scale power plant demonstrations are planned. The first, EBWR, now building, is described in P497. It will yield 5 to 10 MW of power. The second is at present only in the proposal stage and no details are yet available, but it is listed in the table for comparison. It is of much larger power output: 180 MW compared with 5 MW.

The selected average core power rating upon which the EBWR design is based is 25 kW per liter core volume, following the BER experience. The bulk of the fuel is natural uranium (4,536 kg.), "spiked" with 19 kg. of U235 to enable the reaction to proceed with a light-water moderator. Clearly in a national power scheme based on a uranium-to-plutonium breeding economy, or a thorium-to-U233 economy, such a reactor could be spiked with these fissile materials

instead of U235. Provision is made in this reactor for operation with heavy water, which would enable operation on natural uranium alone. Therefore the primary circuit (including the turbine and condenser) is made to an extremely high standard of leak-tightness to avoid D_2O loss. This, coupled with the facts that the entire plant is built inside a gas-tight steel containing building and that provision is made for expansion of total capacity and other modifications, naturally results in higher capital cost than would be the case for a single-purpose reactor built in light buildings in a remote area.

21. *The Heavy-Water Boiling Reactor Proposals.*—In order to use a fuel feed of natural uranium only it is necessary to use heavy water as a moderator instead of light water. To achieve criticality and to operate with the moderator at high temperature it is necessary to use a core 10 ft. or more in diameter, plus 3 ft. or so for the reflector. Therefore such reactors must be used for large heat outputs if the investment charges against fuel and moderator are to be sufficiently small. The pressure-vessel thickness for 600 lb. per square inch working for a reactor of this size would be about 4 in. To provide 600 lb. per square inch steam from a PWR would require 2,000 lb. per square inch core working and provide an almost insuperable pressure-vessel problem. Further, the hold-up of heavy water outside the reactor itself is quite small (steam volume plus condensate only), whereas with a PWR an external hold-up volume almost equal to that within the reactor is unavoidable.

The use of heavy water, with its good moderating power and low nuclear capture cross section, enables the attainment of a conversion factor near to unity, so that reactivity of the fuel may be maintained to a high degree of burn-up provided the metallurgical difficulties can be overcome to permit the long exposure.

To obtain a sufficiently high heat rating from the fuel investment it is necessary to form the elements into thin plates to avoid excessive fuel-element surface heat fluxes. Because of the longer neutron slowing down distance in D_2O as compared with H_2O (because deuterium has twice the mass of hydrogen), it is desirable to space the fuel elements further apart in D_2O than in H_2O, giving water-to-uranium volume ratios of 20:1 compared with 2:1. Further, it is desirable to reduce the surface area of uranium exposed directly to neutrons diffusing in from the moderator volume. This is in order to avoid excessive non-fissioning capture by U238 due to the very high "resonance" capture cross-sections of U238 for neutrons not yet fully slowed down to the equilibrium thermal velocity distribution. Therefore the fuel plates are arranged in clusters so that the outer plates act as screens which absorb such resonance-speed neutrons as diffuse into the fuel element volume. The inner plates are therefore prevented from capturing an excessive quantity of the yet unthermalized neutrons which they would have done if all the fuel-plate surfaces were equally exposed to the diffusing neutrons. This clustering of the plates results in a further advantage. It is only necessary to have high-temperature water circulation within the fuel arrays themselves, so that the bulk of the moderator can be kept cooler (average 90 deg. C.). This enables the thermal neutron velocity distribution to be centered on a lower speed than would be the case with hot moderator, and this, in turn, still further reduces the resonance capture effect (also neutron leakage), and hence the critical size is kept to a minimum (also the conversion factor is raised because of the lower leakage).

The lattice spacing (8 in. centers) actually chosen is a compromise between the need to keep the critical size small (needing large spacing) and to keep the heat output per unit volume of heavy water high (needing small spacing).

The paper also gives studies of some smaller plants (250 MW heat) and compares D_2O and H_2O cases. The authors' conclusions are: *(a)* the 1,000-MW D_2O reactor can produce power at half the cost of that from the H_2O reactor; *(b)* for small reactors H_2O is superior because the amount of D_2O per unit power output becomes uneconomic; *(c)* around 200 MW (heat), H_2O and D_2O are roughly equal economically.

22. *The U.S.S.R. Boiling Homogeneous Thorium Breeder Reactor Proposal.*—In this reactor proposal the use of either natural uranium in heavy water, or enriched or pure uranium (U235 or U233) in light or heavy water is planned, the uranium to be in the form of a solution of salt or a suspension of oxide. It is claimed that experiments have shown suspensions to be a workable proposition and that sedimentation is not a serious problem, being maintained uniform with ease by ebullition.

The main proposal is for a breeder reactor with a thoria suspension blanket, also boiling. Thermosyphon circulation of the fuel and blanket solutions or suspensions is proposed in order to maintain homogeneity and to provide steam separation in a separate drum. It is claimed that an apparatus has been designed to "purify" (presumably to decontaminate of radioactivity) the steam by a factor 10^{10}. It is not proposed to pass this steam through a turbine, but to condense it in a condenser-evaporator heat exchanger.

Besides the usual advantages claimed for the homogeneous thorium breeder of the PWR type, the Russian authors claim *(a)* the hold up of fissile content is less; *(b)* no forced circulation pumps are required; and *(c)* because of the high decontamination factor no significant (delayed) neutron emission occurs in the heat exchanger, so that the steam produced is not radioactivated.

The claim is also made that this class of reactor is both stable and self-regulating, whereas the homogeneous PWR is said to be stable only. This does not appear to be the case, however, to judge from the HTR reports. There is, of course, a difference in the stability of the two classes of system on account of the steam void formation effect being added to the liquid thermal expansion and radiolytic gas production effects in the homogeneous PWR case.

LIQUID-METAL COOLED REACTORS

23. *The Sodium Reactor Experiment (SRE).*—This is an ambitious engineering-scale experiment aimed to demonstrate the engineering aspects of a high temperature (515 to 650 deg. C. outlet temperature) sodium-cooled graphite-moderated power reactor and to carry out the necessary experimental and development work required to lead up to the 75 MW (electric) power reactor (SGR, item 24) also being designed by the North American Aviation Company. The SRE will produce a nominal 20 MW of heat, but no power conversion equipment is being provided initially.

The graphite moderator blocks, hexagonal in cross-section and just under 11 in. across the flats, must be canned in thin (0.035 in.) sheet zirconium in order to prevent absorption of the sodium coolant by the graphite, which would cause excessive neutron losses. The graphite is cooled by flowing sodium over the outside surfaces of the zirconium cans. The insides of the cans are vented to the helium blanket gas space above the sodium surface to ensure pressure equalization, having regard to the possibility of gas production by the graphite when irradiated. It is necessary to subdivide and cluster the fuel elements in order to keep the surface heat flux and uranium central temperatures to acceptable values. Using enriched uranium bars 0.75 in. in diameter the maximum central temperature is kept down to 650 deg. C., and the maximum surface heat flux to about 107 watts per square cm.

It is interesting to note that despite the fact that sodium is well suited to pumping by electromagnetic pumps, in fact mechanical pumps are to be used for this reactor. It seems probable that this has been inspired by the combined desires for ruggedness (avoidance of thin-walled pump tubes) and avoidance of irradiation of insulated windings in close proximity to the gamma-active sodium. Frozen sodium shaft seals are employed, helium blanketed to avoid reaction of the exposed cold sodium with the outside atmosphere.

24. *The Sodium Graphite Reactor (SGR).*—This proposal has now been taken up by the Consumers' Public Power District of Columbus, Nebraska, as one of the four industrial power demonstration proposals submitted by industry in which industry would bear 80 to 90 per cent. of the costs of the program.

The studies described in P493 are based on what are considered to be conservative engineering limitations actually to be attained by the SRE (item 23). It will be seen from the table that the designers believe that this system can be developed to have a conversion ratio of about unity in a power reactor of large heat output (400 MW). Such a reactor would require no feed of fissile material, requiring only thorium from which to create its own fissile U233. The expected performance of this power system may be compared with the potentialities of the aqueous homogenous thorium-to-U233 breeder and the fast fission U238-to-plutonium breeder. The SGR would not generate surplus fissile material as would the breeders, but would be self-sustaining on the thorium feed, and is capable of high temperature operation, leading to high power plant efficiencies of well over 30 per cent.

The use of thorium metal with its superior metallurgical properties as compared with uranium is expected ultimately to enable the SGR type of reactor to produce steam temperatures to the limit of present power plant capabilities. The limitation of such attainment at present is the uncertainty regarding the performance of suitable zirconium alloys in liquid sodium at high temperatures, e.g. 650 deg. C. If neutron economy was neglected and stainless steel used for cladding the graphite, a sodium outlet temperature of 650 deg. C. could be obtained using techniques available at present in a thorium-uranium alloy fueled reactor. The thorium central temperature would be about 1,100 deg. C., which is considered to be entirely acceptable.

25. *The Bismuth-Uranium Liquid-Metal Fueled Reactor.*—This very promising proposal is at present in the preliminary experiment and design study stage. It is based upon the unique property of bismuth that it combines low neutron capture cross section with the ability to take into solution up to about 0.1 per cent. of uranium at reactor operating temperatures, which is sufficient to enable a thermal neutron reactor (but not a fast reactor) to work.

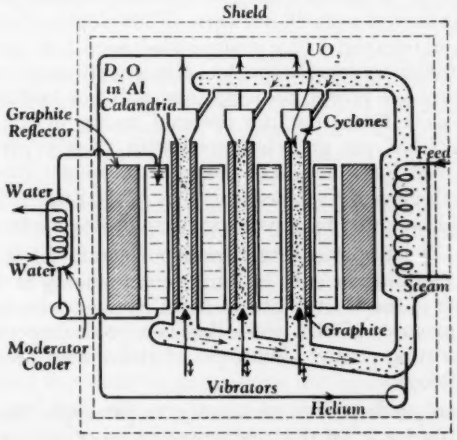


Figure 17. Netherlands reactor system using dry fluidized solids as coolant. Vibrators promote flow.

The advantages of liquid fuel systems have been discussed under 14 and 15 above. This liquid metal system retains many of these (positive breeding gain, continuous processing, complete fuel burn-up, high power density, continuous de-poisoning, etc.) with the added advantages of much higher coolant outlet temperatures and the absence of high pressures. No radiolytic gases are produced.

The primary difficulties at the present time are associated with corrosion, as with the HTR proposals, although these seem well on the way to solution, and the fact that many of the novel techniques proposed have yet to be demonstrated on a large scale.

This led the authors of the paper, P494, to conclude that it will not be until the early 1960s that a full-scale breeder power plant can in fact be demonstrated.

Experiments have shown that the uranium-bismuth fuel solution can be used directly in contact with the graphite moderator, thus avoiding moderator canning (e.g., as required in the SGR) with its associated neutron wastage. Because of the much lower thermal neutron absorption cross-section of bismuth (0.032 barns) as compared with sodium (0.49 barns), absorption of bismuth within the graphite porosity is not serious as in the SGR. It has also been shown that low chromium steel (2.25 per cent. Cr, 1 per cent. Mo) can be used for long-term containment at 550 deg. C. provided small quantities of magnesium and zirconium corrosion inhibitors are employed in solution in the bismuth. The authors consider that these results justify an assumed life of 10 to 20 years for a reactor built on these principles.

26. *The First Fast Fission Reactor to Produce Electric Power (EBR).*—This reactor is of historic interest since it produced the first electric power from a nuclear reactor, although this was in a sense only a heat recovery plant working at the comparatively low thermal efficiency of 17 per cent. Nevertheless, the 200 kW or so of power produced provided power for the building and area. The prime purpose of the reactor was experimental investigation into the principles of the fast neutron breeder reactor system. It was fueled with 90 per cent. U235 clad in stainless steel, in contrast to the plutonium-fueled Los Alamos fast fission research reactor. Since neither of these reactors are power projects they will not be further discussed. Note that the thermal rating of the fuel is 0.027 kW per gm. compared with 1.0 kW per gm. proposed for a 500 MW power fast fission breeder. "The Review of Fast Reactors," by W. H. Zinn (P814), should be noted by anyone studying these systems.

27. *The Experimental Breeder Reactor EBR-II.*—This installation is to be built, commencing in 1956, as part of the United States A.E.C. power demonstration program. Once again this is a bold concept, incorporating many features of advanced reactor technology.

As regards power economics, in principle the fast reactors have all the advantages except, so far, the possibility of a liquid-fuel system. The design study ideas for a 500 MW reactor to be extrapolated from the EBR-II indicate fissile fuel heat ratings of the order 1.0 kW per gm., which may be compared with the ratings of other design study reactors in the following table:

TABLE III

Reactor	Power, megawatts (heat)	Fissile investment, kilograms	Fuel rating, kW per gram (=MW per kg.)
EBR study	500	500	1.0
SGR study	250	360	0.7
LMFR study	550	170	3.2
HTR study	400	30	14.6

It is seen that on fuel rating the large fast reactor shows up well by comparison with the nearest solid-fuel liquid-metal cooled thermal neutron reactor, but not so well by comparison with the liquid-fuel types. This showing is even worse when the external hold-up of solid fuel elements undergoing processing is taken into account. Nevertheless, the large breeding gain factor (1.5) attainable with the fast fission plutonium breeder appears almost completely to offset the apparently increased fissile inventory charge consequent upon the lower rating.

In the fast fission power reactor a large investment of fissile material, diluted to only a moderate extent with non-fissile material, is required to occupy a very small volume compared with most other reactor types. In order to obtain an economical heat rating from this material very high volumetric heat generation rates are entailed, leading to the need to subdivide the fuel into very small diameter rods, with consequent difficulties regarding mechanical support and flow distribution, in order to keep the surface heat flux and the maximum fuel temperature down to acceptable levels. Even so, the average heat flux at the fuel element surfaces is 315 watts per sq. cm. in the EBR-II, compared with 110 watts per sq. cm. maximum in the SRE design.

The engineering features of the EBR-II design are of considerable interest. As will be seen from the sketch, Fig. 16, the whole reactor, together with the primary electromagnetic circulation pump and the primary heat exchanger, and (not shown) the fuel-element storage block, is immersed in a large tank of sodium which is so designed and itself, in turn, contained, as to guarantee that the sodium content cannot be lost by leak or breakage, and in particular, that the sodium level could not fall below the level of the top of the reactor core.

This system offers the following very considerable engineering advantages.

(a) The core is always immersed in sodium, including pump failure conditions, and no circuit failures can violate this.

(b) The large thermal capacity of the sodium filling of the tank can deal with a great deal of heat under fault conditions, and natural convective cooling is available in emergency.

(c) Fuel elements can be changed immediately after shut-down because of the cooling available at all times on account of their continuous immersion in sodium during transfer from core to storage block, thus ensuring the removal at a sufficient rate of the considerable heat output arising from the radioactive decay of the fission products contained in the fuel.

(d) Leaks in the primary circuit are of little consequence; in fact, pipe expansion joints may be made a sliding fit and allow a small leakage.

(e) Although the intermediate sodium-to-sodium heat exchanger is very close to the reactor, because of the neutron shield around the reactor, in fact the secondary sodium does not become radioactive, so

that the only compartment of the plant requiring shielding is the sodium tank itself.

The need to reduce fuel processing costs and the idle investment of fuel outside the reactor has led to the incorporation with the EBR-II of a pyro-metallurgical fuel element processing installation immediately adjacent to the reactor itself. Here the spent fuel elements will be de-canned and melted. It is found that 90 per cent. of the fission products and reactor poisons can be removed by slagging. Since the neutron-absorbing poisons (certain fission products) do not affect a fast reactor to the same extent as a thermal reactor, the residual 10 per cent. may be left in the melt and incorporated in the re-constituted fuel. After the replacement of the burned fissile material by means of suitable additions of plutonium to the melt, the re-conditioned metal is cast and re-fabricated into new fuel elements and re-inserted into the reactor. The whole process must, of course, be carried out behind shielding in gas-tight enclosures by remote control methods because of the gamma activity of the fission products and the combined toxic and radioactive hazards of plutonium and fission products.

A very ingenious design of combined homopolar generator and direct-current electromagnetic pump, the latter portion totally submerged in the sodium, has been designed for this reactor. It is interesting to contrast the coolant system of the EBR-II with the somewhat analogous system employed in the SRE, in which the gamma-active primary sodium is taken right outside the reactor tank and shield, through shielded pipe galleries to the (shielded) intermediate heat exchanger. In this case mechanical pumps with frozen shaft seals are employed instead of the electromagnetic type.

28. *The A.P.D.A. Power Demonstration Proposal.*—The group of companies constituting the Atomic Power Development Associates, Inc., have made proposals for a large-scale fast fission breeder power plant. Its power capacity and approximate costs, taken from a special (unnumbered) paper issued at the Conference, are indicated in the table. Few other details are as yet available, but the sketches given show the intermediate heat exchanger and primary circuit pump (which is indicated as mechanical) outside the main reactor tank. Neutron absorbing material is used for control rods instead of moving fuel element assemblies as in the EBR-II, but otherwise the core design appears similar. The whole plant would be enclosed in a gas-tight building.

29. *The Dounreay Fast Fission Breeder.*—Paper P405 on the Dounreay project deals in a qualitative fashion with the principles underlying the fast reactor project, and outlines in more detail the arrangements being made for the safe containment of the core and the primary sodium under all forseeable conditions. The 60 MW heat rating of this reactor is similar to that of the EBR-II reactor.

Instead of one large intermediate heat exchanger and one large pump all immersed in sodium, the Dounreay plant will have 24 intermediate heat exchangers and 24 electromagnetic pumps situated in an annular (air-filled) compartment around the core but shielded from its neutron emission to prevent radioactivation of the secondary sodium. Each pair of pumps will be powered by one of twelve Diesel-electric generator sets permanently connected to the pumps, thus avoiding dependence upon mains supplies and also all reasonable chance of total failure of the local power generation. To deal with the disposal of shut-down heat in this unlikely event of total power failure each of the 24 pump loops has in series with it a thermo-syphon sodium-to-sodium heat exchanger, with ultimate heat rejection to air via a natural-convection air cooler mounted in a chimney. The whole nuclear plant and primary-circuit equipment is to be contained inside a 135 ft. diameter steel sphere.

No details of the core construction are given beyond saying that the core size will be about 2 ft. in diameter and 2 ft. in height.

MOBILE-SOLID COOLED REACTOR

30. *Reactors Using Dry Fluidized Solids as Coolant.*—A Netherlands paper, P938, outlines three reactor schemes based on the use of fluidized uranium and thorium oxides. The most interesting proposal is for a 300 MW power reactor using cool heavy water as moderator and natural uranium oxide powder flowing inside about 250 graphite tubes which pass through the 10 ft. diameter moderator tank, which is presumably of aluminum calandria construction as for the heavy-water research reactors such as NRX.

The flow downwards through the reactor is promoted by vibrators at the bottom of each fuel channel, where the fuel leaves at a temperature of about 1,200 deg. C. The hot powder is then fluidized with helium, and used to raise steam, after which it is returned to the top of the reactor for recirculation. Some degree of continuous de-poisoning is thought practicable.

This novel reactor proposition is backed by some experimental work on the fuel-flow system, but is as yet nowhere near the state of development of the other reactor types described. Advantages claimed are: *(a)* it is possible to produce high quality steam without the need to pressurize the reactor; *(b)* the cheapest fuel can be burnt in this reactor, namely natural uranium in oxide form; and *(c)* a high conversion ratio is assured with the probability of being able to breed U233 from thorium (oxide).

PROSPECTS

The papers presented to the Conference have reviewed the properties and potentialities of a wide range of power producing reactors. This range probably included most of the reactor types reasonably feasible.

As Sir Christopher Hinton pointed out in his paper, P460, the United Kingdom is at present carrying out full scale experiments at the two ends of the scale of nuclear power reactor possibilities: the simple natural uranium graphite system (at Calder Hall), and the fast plutonium breeder (at Dounreay). Studies are also in progress on other systems which are

thought to show promise, including in particular water-moderated types, as possible successors to the graphite-moderated types.

It would be difficult to sum up the present position as regards the desirability of the various technically practicable reactor types in a better way than by quoting a few paragraphs selected from Alvin M. Weinberg's "Survey of Fuel Cycles and Reactor types" (P862).

"The development of nuclear power and of fossil hydrocarbon fuel both have this in common: there are a variety of possible fuels, a variety of devices in which they can be burned, and a variety of uses to which the energy can be put. Because the development of hydrocarbon fuel utilization has been so gradual, it has hardly been necessary or even relevant to consider the comparative merits of coal, oil, or natural gas. Each is used where it is available; and practical economic considerations determine the relative usefulness of the fuels in each situation.

"Eventually, this will be the case with nuclear energy. Both raw materials, thorium and uranium, will be used; questions of relative advantage will be settled by experience. Because the nuclear fuels are so much less bulky than fossil fuels, it is unlikely in the long run that one fuel will prevail over another simply because of local availability.

"For countries which possess no diffusion plant facilities for re-enriching slightly used fuel, the problem of which system to start with is automatically answered; natural uranium must be the raw material. But this is a temporary situation. The plutonium produced in the natural uranium reactors will be burned in enriched reactors, and it soon becomes a question whether to use the excess neutrons to manufacture uranium 233 or to manufacture more plutonium 239.

"The enormous difficulty of choosing a proper path for reactor development is easily seen by estimating the number of conceivable reactor types. In Table IV are listed some of the choices which are more or less at the disposal of the reactor designer.

TABLE IV.—CHOICES TO BE MADE IN REACTOR DESIGN

Fuel	Fertile material	Neutron energy	Coolant	Geometry	Moderator
U233	Th	Fast	Gas	Hetero-geneous	H_2O D_2O
U235	U	Resonance	Liquid metal	Homo-geneous	
Pu239		Slow	H_2O D_2O Hydro-carbons etc.		Be BeO C, etc.

"Table IV by no means lists all possible choices; yet, the total number of combinations in Table IV is 3 x 2 x 3 x 5 x 2 x 5 = 900 possible reactors! Of course, not all of these are sensible; for example, a fast reactor could hardly be cooled with H_2O. Even so, there are probably at least 100 combinations which are not obviously unfeasible. The central issue in reactor development is to trace out of this welter of possibilities the dozen or so which are most likely to succeed.

"Fortunately, nuclear considerations greatly reduce the number of possibilities. The slow neutron breeding cycle most certainly requires U233-Th; the fast neutron cycle can use either U233-Th or Pu239-U but the latter has the nuclear advantage.

"Will one or two reactors emerge as unique choices? I think every worker in reactor design must have wondered whether, in the long run, any one reactor type will emerge as so distinctly superior to the others that it will render the rest obsolete. The

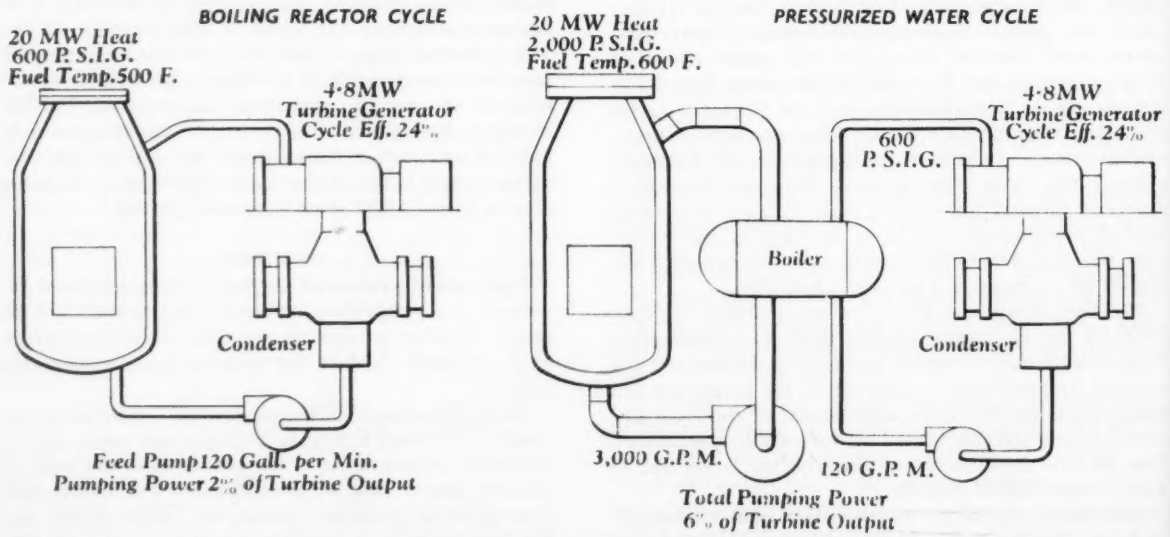


Figure 18. Comparison of the flow cycle of a boiling reactor with a pressurized-water reactor. Larger practicable core sizes are possible with boiling reactors, which are also comparatively simple.

history of hydrocarbon-burning devices suggests that the technology will develop a succession of most desirable types; the reciprocating steam engine was followed by the steam turbine—which may ultimately be replaced by the gas turbine. Within each class —say the steam turbine—there has been a tremendous development and corresponding high rate of obsolescence; for example, the heat rate of the most modern turbines is less than half the heat rate of turbines only 20 years old.

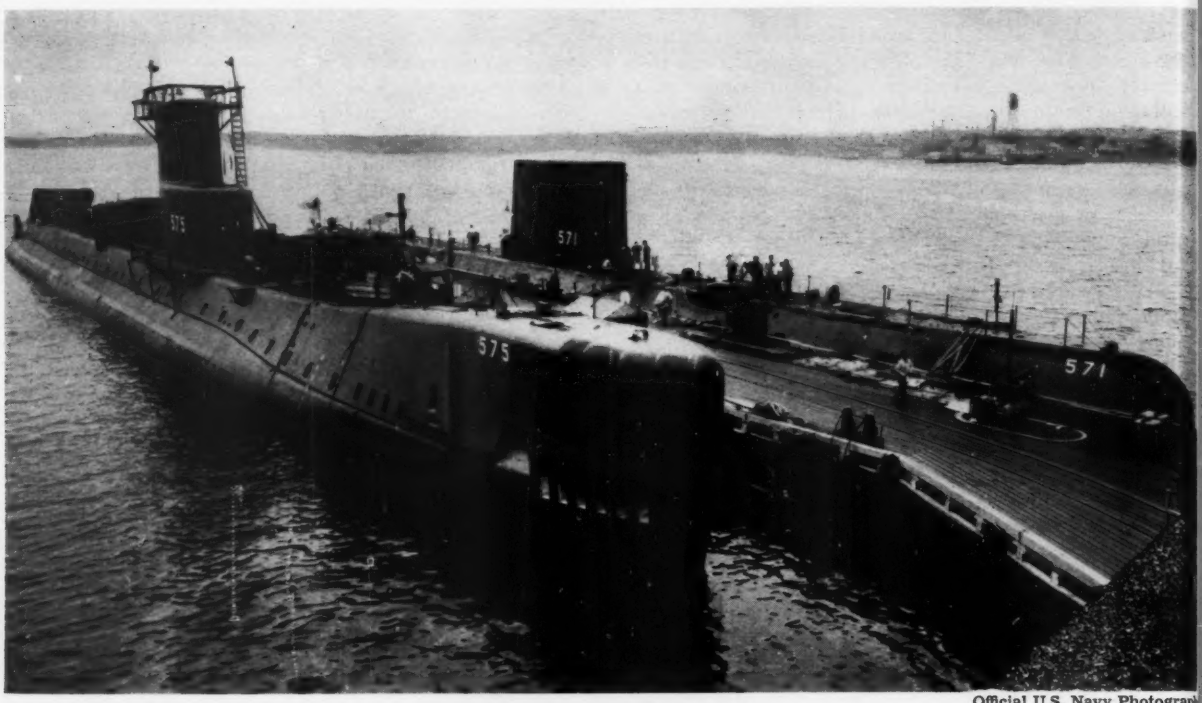
"But the main reason for obsolescence of conventional power generating devices—low thermal efficiency—will hardly operate to render nuclear power plants obsolete. Rather nuclear plants ought to be much more like hydroelectric plants: if they have sufficiently low over-all operating costs, and this is a sum of costs determined by thermodynamic efficiency, material efficiency, maintenance, etc., then it is at least not obvious why they should become obsolete any more than dams become obsolete.

"If all else is equal, that reactor plant is best which operates at the highest thermal efficiency. However, since in each reactor there is always held up a significant amount of expensive material—either fissionable material or moderator—and this held-up material represents a continuing expense, it is also important to extract as much energy from a given amount of fuel as possible. The electrical energy extracted per unit amount of fuel or expensive moderator might be called the 'material efficiency.' In a chain reactor high material efficiency, as well as high thermal efficiency, leads to low over-all power cost.

"What I have said refers mostly to the long run. In the meantime, with highly enriched material something of a rarity, it is inevitable that power will be extracted from the natural uranium systems in more or less conventional reactors. Yet once a reactor is constructed with natural-uranium fuel rods, there will be a strong nuclear incentive, after the first few loadings with ordinary uranium, to switch to the U233-Th cycle. The strong possibility, even in the heterogeneous system, of making the U233-Th thermal system self-sustaining will always be an attractive goal, no matter how plentiful natural uranium may be. Thus it may not really be relevant to argue whether breeders ought to be developed as soon as possible. It seems to me entirely likely that most heterogeneous power reactors which begin their lives as thermal, natural-uranium converters will gradually convert to the U233-Th cycle simply because operation with this fuel is probably independent of raw material.

"In any event certainly two nuclear types, the slow cycle based on U233-Th and the fast cycle based on Pu239-U will become accepted reactor types. Beyond this—whether the reactors will be homogeneous or heterogeneous, whether the moderator ultimately will be D_2O, Be, C, etc., what the coolant will be—these are difficult issues whose outcome no one can foresee. It is of great advantage to our budding technology that it is being pursued—with such little overlapping—in so many different countries, for only out of such diversity in effort will come the answer to the question: 'Which reactor type is best?' "

The world's first nuclear-powered vessel, the USS NAUTILUS, got under way at Groton, Connecticut, on January 17, 1955. Already, the second atomic-powered undersea craft, the USS SEAWOLF, has also been completed.



Official U.S. Navy Photograph

USS "Nautilus" and USS "Seawolf"

Records of attempts to utilize submarine warfare go back to the earliest writings in history (Herodotus, 460 B.C.).

* * *

Aristotle (332 B.C.) and Pliny the Elder (77 A.D.) mention determined attempts to build submersible craft.

* * *

Robert Fulton, inventor of the steamboat, built 2 or 3 submersible warships, one of which was known as the NAUTILUS.

* * *

The American Forces employed a submarine in the Revolutionary War. It was built by David Bushnell at Saybrook, Connecticut, just a few miles from the present site of the U.S. Submarine Base in New London.

ROBERT W. CLACK

POWER REACTORS

THE AUTHOR

graduated from the U. S. Naval Academy with the Class of 1944. His Navy duty, following graduation, included one year in destroyers and 2 and a half years in Naval Aviation. He is now in the Naval Reserve. He was employed in an engineering capacity by the Radiation Laboratory of the University of California for 6 years. After a 2 and a half year interlude at cattle ranching in Southern Kansas, he decided to reenter the nuclear engineering field. The Geneva Conference on Atomic Energy was approaching when this decision was made and it appeared to be a worthwhile opportunity to refresh himself in the field. He attended the Conference as "d'Observateur." Upon returning from Geneva, he joined the faculty at Kansas State College in Manhatten, Kansas. The College expects to undertake a reactor program in which the author hopes to participate.

POWER REACTORS

THE RECENTLY concluded International Conference on the Peaceful Uses of Atomic Energy at Geneva has provided an unique opportunity to bring the broad field of nuclear power into perspective. Two relatively simple views may, properly rendered, afford a much better understanding than a detailed and complex single view. The first presentation, then, is a general description of basic engineering and economic considerations in the field at this time, an instantaneous view with respect to time. The second view may be likened to a panorama of the whole field of power development showing the continuity of development and the manner in which nuclear power fits the picture. The term "power" as used here, refers to the commercial and competitive rate of energy production such as in large, reliable central plants. It seems likely that 100,000 kw of electrical capacity will approach the lower practical limit of capacity of nuclear power plants.

As the Conference opened, it appeared that the great outpouring of technical information was to usher in an abruptly formed new era of cheap power. This promise shone especially bright for poorly developed countries suffering from a shortage of power. Doubts soon formed which dulled that promise. It is now reasonably certain that nuclear power will go no place that fossil power has not gone before it.

Power reactors, in their construction and design, draw heavily on the best engineering skill, fabrication techniques and facilities to be found in the most technically advanced and wealthy countries. A high order of competence is required in the fields of physics, chemistry, metallurgy, electrical engineering, electronics, and mechanical engineering. In addition, a great amount of capital and superior administrative ability is needed. It is not enough that a country just have these skills, but it must have them in sufficient abundance as to avoid crippling other vital activities when these resources are diverted to reactor construction. A measure of the accuracy of this observation can be seen in a tabulation by nation, of the total power capacity of reactors built or building. That figure is a fair measure of the constructing nation's technical-industrial wealth. The Russians have been reticent about disclosing their exact plans which makes difficult a direct comparison with them.

For an industrially poor country, nuclear power is no bonanza but rather a new source of expensive power. Many of the problems faced by a smaller country expecting to enter the field of nuclear power production are quite old fashioned but nonetheless real. As an example, in a well balanced electrical

power distribution system, there should be reserve capacity equal to the largest generating plant in the system to replace the temporary loss of that plant. At the same time, in order to achieve reasonable economy of investment capital, it is undesirable to have idle generating capacity. An example of a practical compromise between these requirements of reliability and economy would be a power distribution grid fed by ten generating stations with the capacity of one station in reserve. If 100,000 kw is the lower practical limit of central station capacity, this suggests a system of 1,000,000 kw total capacity. A 100,000 kw nuclear plant could be readily integrated into such a system. There are few places in the United States or Western Europe where power grids of this size or larger cannot be found. However, such grids are certainly not common throughout the rest of the world. The situation can be summarized, roughly, by the old saw, "It is easy to borrow money at the bank if you don't need it." Thus the United States, in the least apparent need, has taken a lead in nuclear power development.

Much speculation exists as to which reactor design will ultimately prove most efficient. The question beggars an answer. It is comparable to asking which aircraft is best. The question is not determinate. If, after establishing all the attendant circumstances under which the reactor shall be built, then it may be possible to make an educated guess, a design study, as to the best answer. There can be no unqualified answers now. Only operating experience can give a final answer. By the time that answer has been given, the plant providing the experience will be obsolescent. This is not a problem unique in the field of reactor design, however, nor need it prevent us from consideration of the interesting engineering and economic variables facing the reactor designer at this time. The design problem can be likened to a chess game in which each move is dependent upon many other moves in the contest. Complex as it may seem, the problem will yield to a systematic approach.

Two fundamental requirements must first be satisfied. If these conditions cannot be met, it means a return to the laboratory and drawing board. These requirements are safety and over-all economy. The reactor must be safe beyond all reasonable doubt. As to over-all economy, if nuclear fuel does not generate power as cheaply as fossil fuel, there will be no significant nuclear power industry. There is real doubt as to whether nuclear power is competitive in any part of the United States today but there is, even so, good reason to build enough power reactors to determine its exact status and to learn from actual experience where improvement can or must be made to achieve the necessary economy.

As to safety, an important development occurred several years ago, the nature of which is quite interesting. The basic character of a nuclear reaction would make it appear that it must be unstable. All other things remaining equal, the power level of a critical reactor rises exponentially, the way money grows at compound interest or bacteria grow in an ideal culture. The compounding period, instead of half a year as with interest, is about 1/100,000 part of a second. Control in early reactors was possible only because of the phenomenon of delayed neutrons. Control was achieved by mechanical rods which automatically sensed the reaction rate and constantly over and under-controlled to bring about an acceptable average power level. A failure of these controls is an ever present hazard, even with "fail-safe" design. This problem is of such importance that it would be difficult to justify the construction of any power reactor as long as it remained unsolved. The solution was found in the form of what is called "negative thermal coefficient of reactivity." This characteristic makes, or tends to make, a reactor self regulating or stable without the use of mechanical devices. As a refresher and aid in understanding the nature of reactors, a simplified description of the process is offered. A uranium 235 atom, when exposed to slow or moderated neutrons, will absorb a neutron in its nucleus and very shortly thereafter split or fission into two lighter atoms (fission products). When the U_{235} atom splits, it liberates two or three neutrons which are expelled with high velocity. Before these fast neutrons are effective in continuing the reaction, they must be slowed or moderated without being parasitically captured. Heavy water and graphite are two of the best moderators since they have little tendency to capture neutrons. As the fast neutrons lose energy on passing through the moderator, the moderator gains that energy manifested by its increasing temperature.

Self regulation can be brought about because "all other things" do not remain equal when the power level rises. One example of a self regulating design is a water moderated, water cooled reactor. In this example, when the power level rises, the water temperature increases. With increasing temperature, the water expands. The lower density water is a less effective neutron moderator and this reduces the percentage of neutrons which continue to take part in the reaction. Thus the reaction rate decreases and the power level falls. With such a design the stability is no longer primarily dependent upon successful operation of levers, relays, cams and similar devices which, in the last analysis cannot be made perfectly reliable. This is by no means the only problem in reactor safety but it was certainly a major consideration. With this particular problem solved, the other safety requirements are much more easily met. Even so, a power reactor must be designed, and the design successfully tested, to withstand every foreseeable emergency. Actually, there are several designs which are believed capable of withstanding all of these abuses but the attitude of the U. S. and British designers is that one more line of defense would be desirable. As a result, most reactors for some time to come will be housed in heavy steel shells to confine the volume of contamination if an accident should occur. One of the few impromptu opinions offered

by the Russians at the Conference was that they felt this to be a "nervous Nellie" attitude. In any case, the Canadians did, in 1952, have an "accidental power excursion" with their experimental NRX reactor. They are understandably reluctant to explain how it came about, but they do say it was a thousand-to-one shot which just could not happen again. The consequences were not disastrous, as can be seen from the fact that they repaired the reactor and put it back in operation without injury or death. It may be supposed that they got an unsought dividend in the form of a large amount of practical experience in decontamination techniques. For all of that, they presumably thought they had a reactor of acceptable safety. To discover, by accident, that your design is not safe is an experience one wants to avoid.

Reactor designers are rich in the number of distinct types or combinations of types of reactors. It would take a little study to even make a full count of all the possible combinations. At first glance, there are literally thousands of possible designs. Most of them can be rejected off-hand as being manifestly contradictory or impractical. But there still remain a substantial number on which an engineering analysis would have to be made to establish relative merit. The most attractive of these have been selected for preliminary development work, prototype reactor construction, and, in a few cases, actual construction of central station generating plants. In the United States and Great Britain, safety and reliability have tended to outweigh over-all economy, a proper decision. In a general way, there is an adverse interdependence between safety and over-all economy. One or the other can be had, but not the best of each in the same plant. Of course much progress has been made toward achieving both, but this remains a major general concern of reactor designers today. As it stands now, the designer takes a full measure of safety and whatever economy obtainable to go with it.

There are many dependent variables in the over-all economy of a nuclear power plant. The situation is immediately so clouded that an intuitive guess of design combinations would be of little value. Thermal efficiency, neutron economy, total plant cost, fuel and/or heavy water inventory, plant site, disposal problems, and chemical processing are some of the more important considerations going to make up the final summation of over-all economy. The complete formula defies expression let alone an accurate solution. As a result, present predictions of nuclear energy costs are generally stated on a plus or minus 25% basis. This is not nearly close or accurate enough to establish the competitive status of nuclear power plants. It is to the credit of the AEC and interested U. S. industry that real work is underway on power plant construction in spite of this uncertainty. Even if the first plants are not competitive, it seems doubtful that nuclear power would ever mature if full size plants are not built and operating experience obtained. This skirts a political question which has no direct bearing on over-all economy but might be called political economy. If the private utilities and qualified equipment manufacturers made no development effort in this field until after commercial reality was an accomplished fact, it is doubtful that the "public power" faction would willingly let the rewards go to stock corporations. Returning to the matter of technical economy, efficient extraction of power from a liquid or solid is a problem never faced before by engineers. In reactors, this problem is greatly aggravated by the intense level of radioactivity. As a result, present power reactor designs have taken a twenty-year backward step in thermal efficiency. Steam temperatures and pressures are down sharply from current chemical fuel designs. This has been necessary because of safety considerations and the relative youth of the field of nuclear engineering. One way to improve thermal efficiency is to resort to liquid metal coolants or heat transfer agents in the reactor. While the liquid metals, such as sodium or sodium-potassium alloy, permit improved thermal efficiency, they tend to hurt neutron economy by parasitically absorbing neutrons. A slightly artificial view is presented here to illustrate the importance of neutron economy. A fissionable atom, upon being split, generally releases two or three neutrons, only one of which, ideally, is necessary to continue the reaction for the liberation of energy. If the extra 1½ (average) neutrons are wasted, the whole process is automatically defeated from an economic point of view. These extra neutrons, which exist uncaptured only about 1/100,000 part of a second, must be stored for later use in an available form. This "storage" takes place when fertile material such as uranium$_{238}$ or thorium$_{232}$ captures neutrons to become fissionable plutonium$_{239}$ or U_{233}. From the standpoint of neutron economy, an efficient reactor will create as much fissionable material as it consumes. This is only possible because fissionable material releases more neutrons than necessary to sustain the reaction. In a sense, almost the entire value of U_{235}, recently priced by the AEC at $25 per gram, can be assigned to the two or three neutrons which an atom can liberate. This turns out to be 235/2.5 x $25/ gram x 454 grams/lb which equals just a trifle more than $1,000,000 per pound. When dealing with a commodity priced at this level, the need for frugality should be self-evident.

Having stored some of these high priced neutrons for later use in the form, for example, of Pu_{239}, the newly created fissionable material must be removed from the spent fuel by chemical processing. At the same time, fission products are removed from the spent fuel because they are parasitic absorbers of neutrons. This processing is a first magnitude radiochemistry problem, and is handled somewhat differently depending upon whether the reactor from which the fuel came is homogeneous or heterogeneous. In the heterogeneous design, the fuel and moderator are isolated from each other with a coolant flowing between them to carry off the heat of reaction. In such a design, the fuel would probably be long

metallic uranium rods clad in an aluminum jacket to confine the fission products. When processing is required, the aluminum clad fuel rods are transported to a radio-chemistry plant where they are converted to liquid compounds. In liquid form, the spent fuel can be treated to remove the fission products and plutonium, after which the uranium and plutonium are restored to solid form. Then the uranium and plutonium, by remote metalworking, are made up into fuel rods again. By turning to a homogeneous design, this solid-liquid-solid fuel cycle can be avoided. The homogeneous reactor uses liquid fuel, a fact which solves a whole file full of problems in reactor design. In the homogeneous reactor, the fuel and moderator are in solution, and this permits continuous removal of fission products—which tends to improve neutron economy. For every problem solved by turning to the homogeneous design, another one is created. Regardless of which design is selected, the chemical processing is expensive. In the current state of development, the chemical processing alone contributes nearly as much to unit energy costs from a nuclear plant as the entire fuel cost contributes in a well situated fossil fuel plant. If chemical processing is one of the biggest economic obstacles to competitive nuclear power, it is also one of the most likely obstacles to yield to applied science and engineering.

Partly because of the newness of the field, partly because of radiation and corrosion problems, capital expenditures per installed kw capacity in a nuclear plant are likely to be about twice as high as for a comparable sized fossil fuel plant for some time to come. This, of course, adds to the cost of producing power, as does the increased insurance rates on a new type operation which cannot be inspected for signs of weakness or wear.

After all the problems are examined, there might be a tendency to conclude that there are more problems than can be successfully solved in any reasonable length of time.

It is for that reason the instantaneous view may be misleading. If the designer cannot see precisely where future progress will take him, at least he can judge the nature of his progress by looking back. In terms of some equated constant unit of purchasing power, the cost of mechanical energy has dropped at a steady, predictable rate since the beginning of the industrial revolution. Although our own chemical energy resources seem to be in generous supply, it would take a remarkable optimism to suppose that we would not need to supplement this chemical fuel if energy costs are to continue to decline. Sooner or later the cost of chemical energy will start to increase as the supply becomes short. England may be facing that situation now. Considering the opportune appearance, in point of time, of nuclear power, it appears that the Master Engineer intends the cost-time trend of energy to continue to drop.

There has been some uneasiness about the impact of nuclear fuel upon the market for coal and oil. While it may be premature to suppose that some adjustment will not be required, the position of oil is certainly secure. Automobiles and aircraft will operate on liquid chemical fuels for many years to come. It is, in fact, most difficult to imagine how individual reactors could ever power automobiles in any practical way. As for aircraft, nuclear power can surely be adapted, given sufficient development work, but for one drawback and that is the consequence of a crash in a populated area. Nuclear power may well come, and soon, for large military aircraft but it is hard to imagine how it could be justified in commercial aircraft. The future of coal may be a little more obscure, but even here the adjustment may be no greater than that brought about by the increased use of oil in the last few years.

There has been some high placed pessimism on the subject of marine nuclear propulsion, and that seems strange, since such development is an accomplished fact. Standing on the outside, looking not in but at the drawn curtain of security, we can still speculate about what may be inside. As with stationary power reactors, there are only two problems which need to be solved, safety and economy. Of course, the long view that reliability is part of economy must be taken to make this assumption valid. It is a reasonable assumption that nuclear propulsion appeared first in submarines because of a special dispensation which relieves a submarine reactor from the same economy requirements as other reactors. Power delivered independent of oxygen is obviously worth more in submarines than restrictive chemical fuels. As for safety, the U. S. Navy has been safety conscious for many years, and it seems unlikely that nuclear propulsion will bring a sudden departure from this policy. Nuclear propulsion may justify substantially increased fuel costs for surface craft, if range and/or endurance can be significantly increased without other penalty. It is reasonable to suppose that such increase in range is already assured, and that the fuel costs, although at present higher than for chemical fuels, can be justified.

If this is true, only uncertain safety stands in the way of a nuclear powered Navy. Granted that there is no absolute safety, what sort of odds are necessary to justify nuclear power in surface vessels? It is true that battle damage to an operating reactor is an unpleasant thing to think about, but so is battle damage to a powder magazine. War has always been a hazardous undertaking. Nations have some chance of avoiding war but no chance of making it safe. The United States has the stimulus and means to have a significant surface reactor propulsion program under way for its Navy, and this program should have borne fruit by this time. Perhaps it has. Regardless of our exact position at the present time, a relative position of "second" in this race is not good enough.

SCIENCE, TECHNOLOGY, AND MANPOWER IN THE NAVY

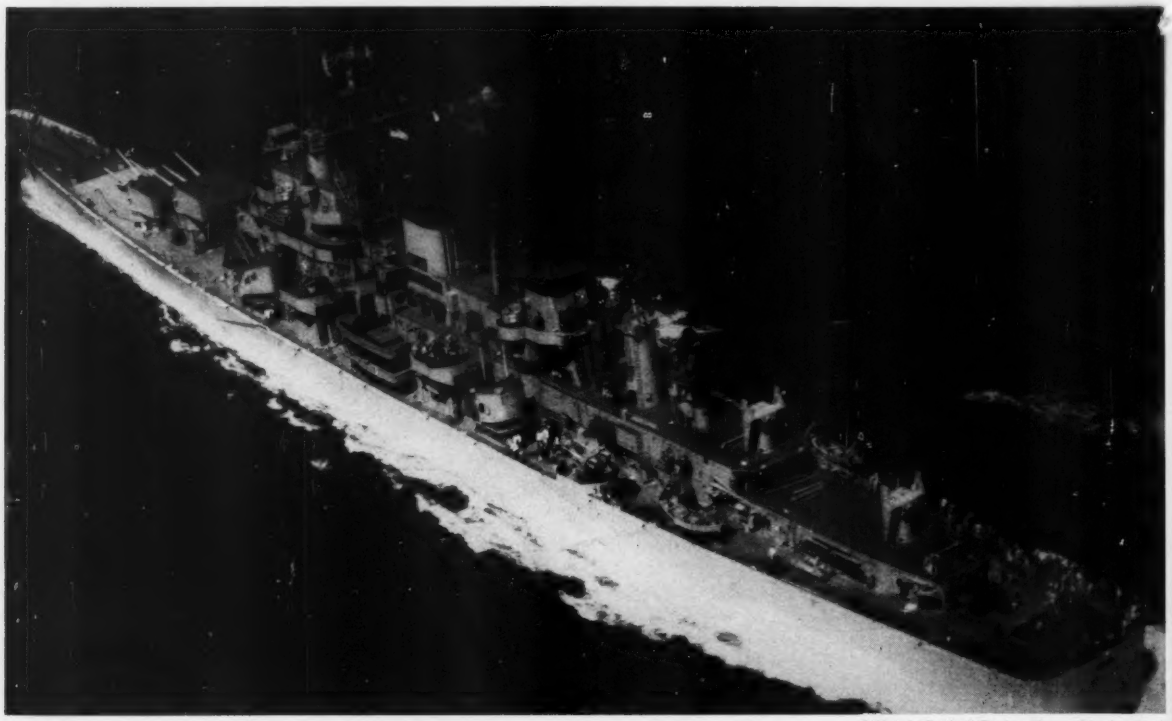
REAR ADMIRAL RAWSON BENNETT, USN
Chief of Naval Research

THE AUTHOR

was born on June 16, 1905, in Chicago, Illinois. He was appointed to the U. S. Naval Academy, Annapolis, Maryland, from California in 1923. Graduated and commissioned Ensign on June 2, 1927, he subsequently advanced to the rank of Captain, to date from March 20, 1945. In December 1955 he was appointed Rear Admiral, to date from January 3, 1956. Following graduation in 1927, he joined the USS California, *flagship of the Battle Fleet. Later, in 1928, he was assigned communication duty on the staff of Commander, Battle Fleet, serving as such until August 1930. In November of that year he reported on board the* USS Isabel, *for duty on Asiatic Station, and in October 1932 was transferred to the* USS Rochester. *He completed his Asiatic tour of duty in the* USS Houston *in 1933. Detached from this vessel, he returned to the United States and joined the* USS Idaho. *After 7 years of sea duty, he returned to Annapolis, Maryland, for postgraduate instruction in radio (electronic) engineering. He completed the course in May 1936, and was assigned to the University of California, Berkeley, for additional postgraduate work, receiving the Master of Science degree in Electrical Engineering, after which he reported aboard the* USS Concord. *Continuing sea duty, he joined the staff of Commander Destroyer Division Nineteen (later redesignated Destroyer Fifty) in April 1938, and served as Radio and Sound Officer until June 1941. Starting in July 1939, he set up the technical program of the first fleet Sound School at San Diego, California. In July 1941, he reported to the Bureau of Ships, Navy Department, Washington, D.C. There he served first as Head of the Underwater Sound Design Section of the Radio Division, and later Head of Electronics Design Division, from 1943 to 1946. He was awarded the Legion of Merit "for exceptionally meritorious conduct" during this tour of duty. Upon leaving the Bureau of Ships in August 1946, he reported as Director of the U. S. Navy Electronics Laboratory, Point Loma, San Diego, California, where he accomplished the post-war expansion of that Laboratory. In July 1950 he was ordered to Washington, where he set up and become the first Director of the Electronics Production Resources Agency of the Departments of the Army, Navy, and Air Force. In October 1951 he reported to the Bureau of Ships, Navy Department, where he was assigned duty as Head of the Mine Warfare Branch. Under orders of March 20, 1953, he next served as Naval Inspector of Machinery and Naval Inspector of Ordnance, General Electric Company, Schenectady, New York. On November 24, 1953, he was ordered again to the Bureau of Ships, for duty as Assistant Chief of the Bureau for Electronics. In December 1955 he was appointed Chief of Naval Research, with the rank of Rear Admiral, taking office on January 3, 1956. He is a Fellow of the Institute of Radio Engineers, a Fellow of the Acoustical Society, and a Fellow of the American Association for the Advancement of Science. He is a registered professional engineer, State of California. This article was prepared and is published as a contribution to the Navy's Recruitment and Reenlistment Campaign.*

WHEN THE NAVY was selected to carry out the technical program for the earth satellite, it was symbolic of what is happening to our modern Navy. It foreshadows a step beyond the familiar bounds of our planet and into space. The Navy is not going to have space ships for a long time, possibly never, but consider only the scientific and technological advances associated with a satellite launching, and possibilities for the future seem almost fantastic.

The Navy, as one of the world's largest technological organizations, makes constant advances in every phase of naval operations, from complex fire-



Official United States Navy Photograph

Figure 1. Aerial view, port side aft of the USS Boston (CAG-1) underway.

control systems to the use of electronic computers in advanced hull and propulsion design. With the conversion from sail to steam, the change from wooden hulls to steel, and the development from round-shot to guided missiles, naval technology advanced rapidly in nearly every direction. Now, with the advent of nuclear power, jet propulsion, and guided missiles, an entirely new concept of naval power is evolving. The basic premise of employing a ship to provide the platform for the weapon has not changed, but the nature of the platform and the weapon has changed considerably. Almost every phase of shipboard life, down to the packaging of food and supplies and the colors used in painting living spaces, is approached from a scientific standpoint.

This new, scientific navy has enormous demands for technical skills in maintenance, operating, and evaluation personnel.

To illustrate the magnitude of what the Navy plans to do and the speed with which changes are projected, compare the expected buildup of nuclear powered vessels with the conversion from sail to steam:

Our first navy ship to be propelled by steam was the *Demologus,* designed and built by Fulton in 1814. For the next twenty years only one additional small naval vessel was powered by steam. The Navy built its last sailing ships many years after the *Demologus.*

Now look at the present: The*Nautilus* was launched in 1954. Six other nuclear submarines are already abuilding and six more, plus a nuclear powered cruiser, have been requested for the 1957 program. By the early 1960's all major naval vessels authorized for construction may be propelled by nuclear power.

Meeting this goal will require major technological advances. The *Nautilus* has more than lived up to expectations, but her atomic power plant represents only the beginning in design. We need rapid progress in the development of new uranium alloys for use in reactor cores; greater understanding of reactor physics, of heat transfer, and of the effects of radiation on materials; development of new and improved components such as valves, pumps, heat exchangers, and instruments.

In developing the *Nautilus* and the *Seawolf,* ordinary methods of science, engineering, and production were not entirely adequate for the rigid requirements. Needed materials were not available, so existing materials had to be used under new conditions. Basic components of the reactor plant such as pumps, valves, and instruments could not be ordered from stock, so engineers were forced to undertake large-scale development and testing programs. Technical information that one might expect to find in the handbooks was lacking; that which did exist was sometimes incorrect. In short, they had to start nearly from scratch and develop new areas in metallurgy, and in physics, as well as a virtually new branch of heat transfer and hydraulics. New approaches by scientists, by engineers, and by administrators in industry and in government were needed. Even the welders, pipe

fitters, machinists, and other skilled workmen found that conventional standards and practices were not adequate for this new job.

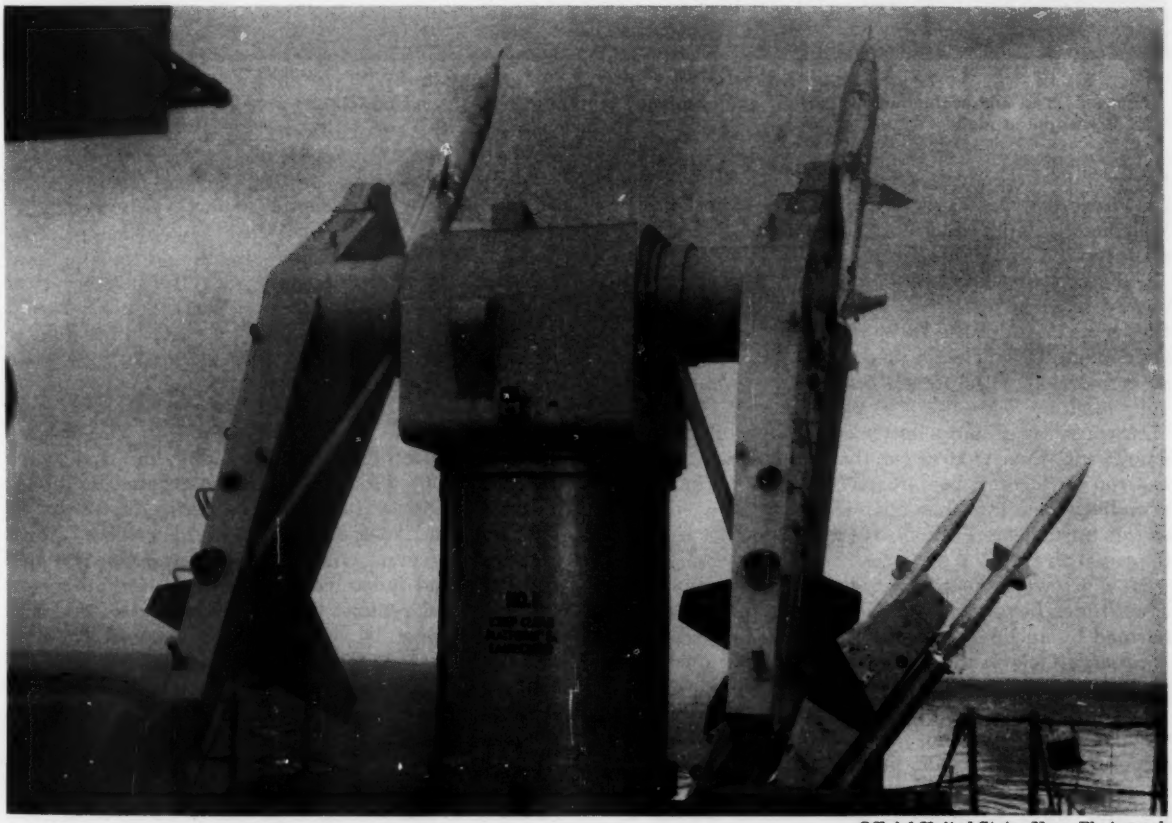
The development of nuclear powered vessels will inevitably generate radical changes in shipbuilding, in construction techniques, and in machinery plant design. The shipbuilder is faced with an entirely new order of structural and arrangement problems because in a nuclear powered ship the reactor should be completely integrated with the hull, just as the engine and the frame of a fighting plane must be designed together.

The *Nautilus*' brilliant performance has made obvious the need for other technical advances to match the capabilities of her revolutionary power plant. The Navy needs better sonar and radar equipment, better torpedoes and missiles, better hulls, and better propellers. A whole new vista of technical requirements is emerging. Just as the invention of the automobile opened up the need for a host of new industries, such as petroleum, glass, rubber, and highway construction, so does the *Nautilus* signify the start of many new technological advances in the Navy and thus, inevitably, throughout industry.

The rate at which these advances are being made is constantly accelerating. The time elapsing between the birth of a scientific concept and the critical experiment is no longer a matter of years. It may be as little as a week. This acceleration has forced the Navy to become deeply involved in science. We cannot merely be a spectator, standing by to purchase any results that look good to us. The Navy must actually be in science, conducting its own work and supporting the work of others.

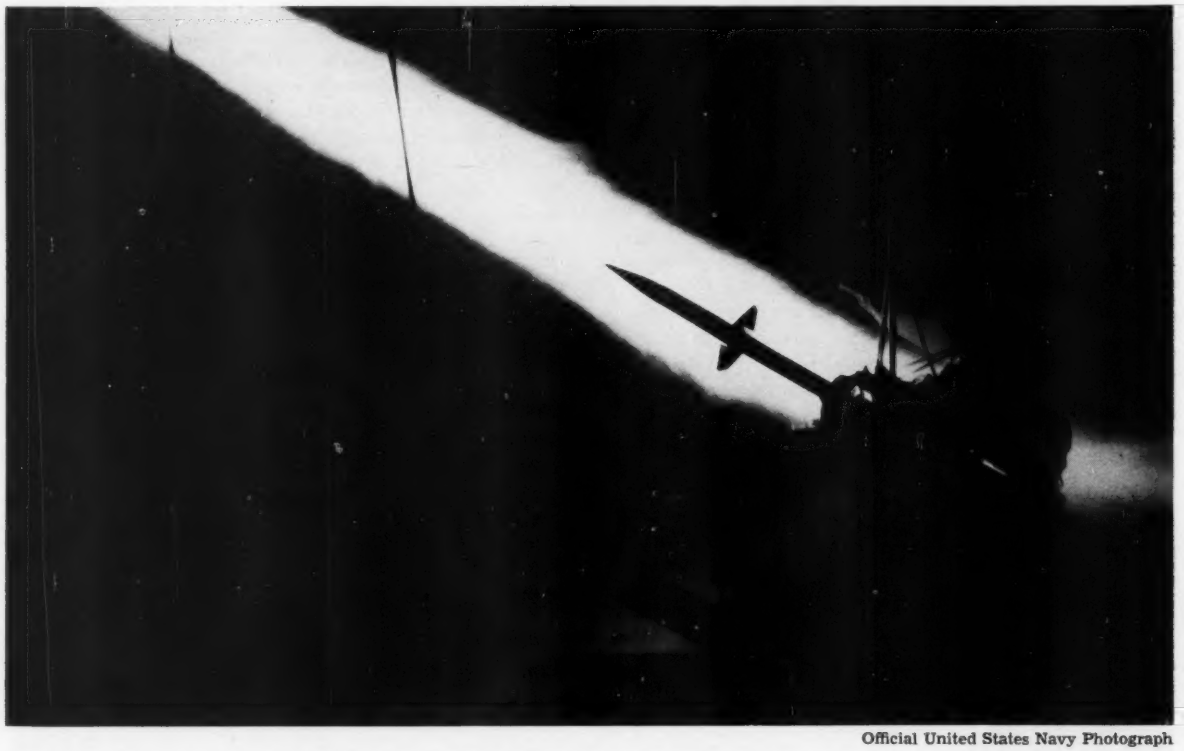
The Navy maintains its own laboratories to perform development and research peculiar to the Navy's needs. It has aviation test facilities, medical research units, an ordinance laboratory, electronics laboratory, underwater sound laboratory and a hydrodynamics laboratory. Laboratory research workers are investigating epidemic diseases in Egypt, corrosion resistance in Panama, and Arctic environmental conditions in Alaska. Wherever the Navy's ships and planes may be sent, whatever the Navy's ships and planes may be called upon to do, they can feel reasonably confident that the peculiar needs of place and circumstances have been anticipated and investigated.

Laboratories of other Government agencies help to supplement the work done in our own facilities. The universities are a primary source for the real pioneer-



Official United States Navy Photograph

Figure 2. Installed aboard the USS Boston (CAG-1), the Navy's new guided missile cruiser, is the Terrier. This missile was tested operationally in 1954 from the nation's oldest battleship, the USS Mississippi. Now aboard the USS Boston, the slim, needle-nosed supersonic weapon is designed to intercept aircraft under any weather conditions at considerably longer range in higher altitude than conventional anti-aircraft weapons.



Official United States Navy Photograph

Figure 3. Test and evaluation of "Terrier" guided missiles by the USS Mississippi (CAG-128) at sea. Terrier launched from USS Mississippi at night.

ing work that replenishes our pool of basic knowledge. Private industry has great developmental capabilities. It is our principle source of the final development of prototype equipments leading to production.

Advanced research is the necessary forerunner of steady material progress. The scientific research of the Department of the Navy should provide a flow of fundamental knowledge of the sort the Navy needs in connection with present and future weapon developments.

How can we obtain a better conversion of chemical energy into thrust? How can the power of the nucleus be used for aircraft propulsion? Is there, perhaps, an even better method than chemical or nuclear energy, as yet unsuspected, for obtaining the thrust needed to propel aircraft?

How are we to keep aircrews and passengers alive at altitudes beyond the earth's atmosphere, and unharmed by enormous acceleration and deceleration? A broad attack on the problems of aviation medicine is underway in an effort to find the answers.

Basic research has given us samples of "perfect" metals, metals without flaws in their crystalline structure. They contain in actuality the enormous strength that theory predicts metals should have. Can we find ways to produce such perfect metals in quantity?

These are some of the questions that bear on the Navy's future. Advanced research will help find answers that can pave the way for development and production of tomorrow's weapons.

The post-war progress of the Navy has been closely geared to the progress of research and development programs. New developments at different periods of history have altered navies almost beyond recognition, and now we appear to be on the threshold of changes that can make sea power more formidable than ever before.

THE MANPOWER SITUATION

The advanced technology of today, and that which we foresee for tomorrow, must be created by highly trained scientists and engineers. Its products must be operated and maintained by highly trained technicians. Everyone who has considered the Nation's scientific and technical manpower situation, even casually, now realizes that a shortage exists, and that it will get worse.

The military research administrator and his personnel staff have been grappling with the problem for several years. So has the industrialist who hires scientists and engineers. The entire educational profession is alerted to the problem, and it has been brought to the attention of civic-minded service organizations and other groups with no direct interest in manpower shortages, but who have a general concern for the welfare of the country. Perhaps the realization that Russia is training greater numbers of scientists

and engineers than the United States has helped to spark the sudden growth of interest and concern in this problem.

The problem has arisen because the American economy is based upon a steadily expanding technology, nourished by extensive scientific research and development. As new industries and new techniques resulting from research and development are gradually built into the economy, more technically trained people are required merely to keep it operating. The problem has been compounded by the urgent demands of military research and development, to support a defense effort that may have to be sustained for many years.

Examine a cross-section of almost any industrial area, any military service, in fact, virtually any segment of the national economy, in terms of technically trained manpower. We find that from top to bottom the need for such manpower is growing. At the top, we need the few truly creative individuals who deal in the realm of ideas. They contribute the bold new concepts, the fundamental breakthrough upon which new technology is built. Next is the great area that includes what we may call "master" or "journeyman" scientists and engineers. Here is the real body of American scientific and technical resources. These men and women comprise the group we usually mean when we discuss the technical manpower shortage. Their number is estimated at about 850,000.

Beyond this group is that part of the cross-section represented largely by operating and maintenance employees. As the system grows technically more complex, the need for trained employees is felt more keenly in this area. As mechanical and electronic equipment takes over more and more of the production process, industrial employment will emphasize knowledge and understanding rather than simple manual dexterity and muscle power.

Advances in military technology have greatly sharpened the need for large numbers of highly trained technicians in the Armed Forces. Tables of jobs for enlisted men show many changes that reflect this trend. Old jobs have been deleted, new ones added, and training time increased. "Guided missileman" and "Aviation fire control technician" are typical of the new enlisted jobs in the Navy. Each has a training time of about 25 months. In radar maintenance, the Army required three specific jobs in 1949. Today it requires seven.

Naval requirements for scientific and technical manpower are best demonstrated by historical contrasts. A survey of occupational groups indicates the percentage of enlisted ratings which would fall in this category:

Period	Technical Manpower % of All Ratings
Civil War	2.8
Spanish American War	2.9
World War I	2.5
World War II	6.4
Korean Conflict	10.8
1954	13.4

Official United States Navy Photograph

Figure 4. Navy's F11F-1 "Tiger."

Based on an estimate of the size of the Navy and the technological advances which are anticipated, it is estimated that the ratings considered as "technical" will comprise about 40% of the Navy enlisted strength in 1960. Obviously, when the services have a man for only two, three, or four years, a good high school grounding in basic technical subjects will relieve much of the strain on service training schools and give us a better technician.

The training needs of each of these categories, from PhD to technician, must be considered in any program or set of programs that hopes to deal with our growing shortage of scientific and technical manpower. We must ensure that the gifted few who can lead us to new understanding of natural laws are discovered and are able to contribute at the peak of their abilities. We must provide for the education of the thousands of scientists and engineers required by our research and development effort. And we must nurture the growth of trained sub-professional workers, to ensure that we are not creating an industrial and military establishment so complex and sophisticated that we have forgotten to provide people to operate and maintain it.

Technological advances increase geometrically, whereas the number and quality of trained personnel can increase only arithmetically. As never before in its history, the Navy is in danger of suffocating itself in its own scientific complexity. The pressure can only be relieved by substantial increases in its trained technological personnel.

To illustrate the rate at which the need for personnel has grown, nine men were required to man the revolving turrent guns on the *Monitor* during the famed Civil War battle in Hampton Roads; today there are many times that number necessary to man the gun mounts, fire control and related systems of a destroyer's five inch guns. At the close of World War II, the guided missile was mostly in the realms of experimentation and speculation; recently the USS *Boston* was recommissioned, the first U. S. ship designated a guided missile ship. Of the 1635 officers and men on the *Boston* 103 highly trained men will be designated missile specialists.

The *Boston* which is a converted *Baltimore* class cruiser, has roughly twice the allowance of gunner's mates, fire control technicians, and electronics technicians of other cruisers of that class. Cruisers of the *Boston* class, not guided missile ships, have seen an increase of allowance for Electronics Technicians from 7 in 1942 to 33 in 1955. This is merely an indication of the direction of technical manpower requirements, since the number of technical ratings other than ET has grown correspondingly.

The challenge of revolutionary and highly developed weapons systems to the established tactical and technical concepts is unprecedented in naval history, bringing with it numerous problems, both foreseen and unanticipated, and vast requirements for personnel with specific training. Trained manpower with the most specific instruction must be made available to the fleet in a never-ending stream. We are in a competitive race for technological supremacy; trained manpower on every level is the vital element for which there can be no substitute.

The young high school graduate of today has a wonderful opportunity before him. For, while he is performing his obligated military service, he can benefit both himself and the Navy by utilizing this period for specialized training in one of the more than twenty-five technical billets open to young men in the Navy. There is an almost limitless field for the student with particular aptitudes for science or technology, and it is an ever-expanding field of endeavor.

During his Navy enlistment, a young technician has the opportunity to broaden his scope in the various fields of technology and keep up-to-date on the newest developments in the various engineering disciplines. He receives training unparalleled in latitude and equipment, while he lays the groundwork for excellent job opportunities or further study.

A look at current statistics is not a reassuring one. At the end of fiscal year 1956, only sixty-seven percent of the minimum estimated electronic technician petty officer strength required will be on board; with increased attrition rate and fewer enlistments, since the cessation of hostilities in 1953, there is a consequently smaller group of specialized petty officers from which to draw. The percentage of high school graduates and average classification scores have decreased radically since the 1949-50 peak of 75% and 60% respectively, to 20% and 43% respectively, in May of 1955. The number of Navy ratings which require special technical qualifications have increased from 28 prior to World War II to approximately 46 at the present time.

The newspapers, radio and television devote much time to discussions, centered around the problems of youth, with psychologists, teachers and the youths themselves. Two factors are outstanding: first, the youth of today are definitely interested in finding their places in the world and are attempting to realize and meet their obligations as young Americans; and secondly, the problem of facing certain military service is one in which they want to be guided, so that they may be enabled to turn this service to their own positive good. At no time in history has science been so important as now, yet there is clear evidence that high school study of scientific subjects has declined. A spokesman for the chemical industry has expressed concern that the percentage of high school students studying chemistry has barely held its own, in spite of the growing need for chemists. The percentage of high school students studying physics dropped to five percent in 1952 and the percentage studying plane geometry has declined steadily every year.

A great proportion of the nation's scientific and engineering potential is not being trained, and is lost to the needs of Government, industry, and the universities. If ways can be found to increase the motivation of young people to pursue technical studies and become trained scientists and engineers, we can narrow the gap between the nation's growing needs and its supply of technically qualified manpower. The

percentage of technicians who leave the Navy and go on to college is relatively small, but without the technician working under him to implement the basic research and design, the engineer and scientist lack the realization of their work as would the architect without the brick mason or the composer without the musician.

The Navy is not trying to drain the seriously low reservoir of technical manpower of the country: it wants to train technicians and thereby help the scientists and engineers of the nation by providing young technicians with incomparable training and experience. Then, in the event of mobilization, there will be a resource from which to draw both for military and civilian service in all technological fields.

In the field of electronics, for instance, future technicians can be trained in radio, radar, sonar, loran, television, or guided missiles to name a few. Some 3700 different types of electronic equipment alone are used daily throughout the Navy, most of them highly intricate and complex pieces of the latest in electronic design. The educational institutions of the country, as well as industry, recognize the value of Navy electronics training. Since World War II, when the Navy trained thousands of men in the shortest possible time with outstanding results, it has increased its ability to provide utilization of the newly developed equipment which pours from the laboratories and industry. It can provide unhurried study under experienced officers, an increasingly large number of whom are awarded graduate degrees in many fields of study from the outstanding technological institutions of the nation.

The Navy training schools are, for the most part, separated into three classes, "A", "B", and "C". The two Navy class "A" schools for electronic technicians are divided into three types of courses: radar electronics for 26 weeks; communications electronics for 24 weeks; and electronics peculiar to sonar, also for 24 weeks. Men who are eligible for a course in a class "A" electronics school study basic electricity and electronics and the repair and maintenance of the course type equipment. Eligibility is determined by the individual's aptitudes and abilities. Last year roughly 22% of those completing recruit training went directly to class "A" schools of all types. Few are ever refused an opportunity to attend a school, if they qualify. The class "B" school for the more advanced technicians includes studies in advanced electronics theory and maintenance procedures, and the class "C" schools have specialized courses for particular phases of electronics and types of equipment. During fiscal year 1955 almost 11,000 student years were spent in these training schools by USN personnel.

Varied opportunities for study outside the class schools include fleet training schools, correspondence schools and individual senior petty officer instruction. Assignment with completely modern research and testing laboratories would enable a man to gain a view of science which he would not achieve by going immediately from high-school to industry. Certainly, most technicians serve with the fleet where they are most strongly needed, but there a young man, thoroughly trained in his own particular field, is given responsibility for maintenance, and operation that would be hard to duplicate in industry. By this enforced technological maturation, those with real ability are advanced above and separated from the disinterested individual. Partially from this, the Navy gains much of the respect it has earned for its training programs.

Once a highly mechanized system, such as a guided missile system for example, has been developed, we cannot think in terms of the weapon alone, or the man alone; they must be considered as a man-machine system. A new weapons development always creates a host of personnel problems: How many men are needed and what skills must they have? What courses should go into the training program? What tests will quickly tell whether or not a man is qualified? Therefore, the Navy's personnel research programs are tailored to meet the immediate needs of the problems created by technical advancements. The personnel research in connection with the guided missile development is a good example of what is being done in this training area.

Personnel research kept close pace with actual missile development. The knowledge and skills men would need to operate a new missile system were analyzed, then compared with the knowledge and skills available in our existing manpower. As a result, it was possible to develop a more efficient job structure, to develop techniques for choosing men, to develop training devices and to develop tests of on-the-job-efficiency.

One of the first outstanding changes in structure to evolve from the guided missile program was the establishment of the guided missile-man rating. Basically, the guided missileman's duties are to assemble, test and maintain the many components of the guided missile systems. His training, at first, approximates that of the electronic technician, then he specializes in various guided missile features. For class "A" training, the majority of the men trained are taken from recruit applicants. At the present time, the facilities limit the capacity of men to be trained in class "A" work to twenty a month; the Bureau of Personnel is swamped with requests for training at this school. A new school is being built at the Fleet Air Defense Training Center, Dam Neck, Virginia. When it is ready for use early in 1958, the backlog of requests can be wiped out.

One of the chief difficulties met in training men as guided missilemen was the situation that existed when the program started. Prototype missiles were being developed at the same time they were being studied; a factory training program was initiated whereby the men entering this new field studied the equipment as it was undergoing change. The rating of guided missileman was incorporated in the fall of 1954. At this time the men, primarily gunners mates, electronics technicians, and fire control technicians, who had been studying in this field switched their ratings.

Another example of Navy training, on a more ad-

vanced level, is illustrated by the situation met by Rear Admiral H. G. Rickover when the *Nautilus* was being developed. He states that, "In our work, as in every venture, trained people are essential. In the early days, and over the protests of many leading people who did not want to interrupt their work, I sent many of them and also our new young people away for advanced technical training in nuclear engineering. At the time it seemed the wrong thing to do because of the extremely heavy work load. But we knew that we had to develop many technically qualified people if we were to become an effective organization. Similar educational steps had to be taken by our contractors. Those of us who remained behind had to carry the burdens of the ones who went away to learn, but we became stronger for it. The benefits from this technical training convinced me that it should be continued. As a result, nearly everyone who has joined us since the beginning, in 1948, has been sent away for additional training."*

The members of the American Society of Naval Engineers can help alleviate this acute technical manpower shortage, both in the Navy and in the scientific world as a whole. Because of their eminence in the engineering fields, their opinions are of great value to young men whose interests and aptitudes lie in science and technology. All the information which has been presented here is worthwhile only if it has served to point out, from the Navy standpoint, how rapidly we are progressing and how severely we need a growing reservoir of personnel. Today's scientific advances do much to shape tomorrow's Navy, but without the technical manpower to man that Navy, our position can become serious.

Each member of the Society can help by accepting requests to speak at young people's and parents' groups. They can point out the opportunities open to young men in the scientific disciplines, and stress the many rewards, intellectual and financial, to be gained from scientific occupation. Many high school students could be urged to study science in college. To others, either not college material or who want to fullfill their service requirements before going to college, service in the Navy should be pointed out as an excellent training ground for basic technological instruction.

Navy training is not an answer to the technological manpower problem in industry, but it does afford one of the best possible opportunities for establishing areas of scientific interest in the individual, for fixing that interest, and for starting the necessary training. If each member of ASNE would influence four young men to take advantage of the Navy's opportunities during this year, there could be almost 12,000 new technicians.

*The paper from which this quotation is taken will be found, printed in full, on pages 17 to 21 of this issue. It will be noted that Admiral Bennett drew on Admiral Rickover's paper in other places also.

There are over 800 Navy schools, specializing in a multitude of subjects aimed at the education of the modern sailor.

T. HARVEY EVANS

FULL SCALE SHIP STRUCTURAL EXPERIMENTS AND THE EFFECT OF UNFAIR PLATING IN TENSION

THE AUTHOR

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SUMMARY

1. Basic heart of plate stress distribution across a ship cross section complies well with simple beam theory but with local deviations sometimes evident in such locations as fore and aft stiffener attachments to plating.
2. While both riveted and welded ships experience occasional structural difficulties, they have been more numerous and severe in welded ships. In welded vessels cracks appeared both to initiate and to propagate more readily.
3. Poor welding workmanship, poor design details, inadequate material or physical and metallurgical notches do not appear to satisfactorily provide the full explanation of welded ship failures.
4. Plating panels which are unfair in the unloaded condition of the ship are more prevalent in welded construction than in riveted. When loaded, the stresses sustained by such panels depart from the stress distribution predicted by the simple beam theory and cause a lack of uniformity of stress that may contribute to crack initiation and crack propagation.

INTRODUCTION

STATIC experiments on ships in still water have had as their primary objective justification of the validity of simple beam theory when applied to the complex ship hull girder as represented by the longitudinally continuous material of the "midship section." Varying, of course, with the availability of ships, personnel and financial support, measurements of longitudinal ship deflection and strains in a girthwise plane (generally in the region of maximum bending moment i.e., about amidships) have been measured for known applied external loadings. Stresses inferred from the measured strains then permit the effective section modulus and moment of inertia to be deduced.

Measured deflections when related to the second integral of M/EI afford another means of checking the assumed values of the product EI. This procedure led some earlier investigators to the conclusion that to reconcile measured and calculated values of deflection, a reduced value of the modulus of elasticity must be used in place of that usually associated with steel. However, widespread rivet slip and structural hysteresis as arguments in favor of a reduced modulus are little in evidence. Recent investigations lend support to the now generally accepted view that any lack of agreement is due to an erroneous evaluation of the effective moment of inertia. For example, some of the material usually included in the calculation of the section modulus may not be fully effective. This view is generally confirmed by the value of the moment of inertia inferred from strain analysis.

The first extensive static experiments were carried out on the 200-ft. transversely framed British destroyer "Wolf"* [1] in 1903, and while in many re-

* Salient features of all the ship data referred to are contained in the table and the figures, following the Acknowledgement.

spects setting the pattern for subsequent work, many questions were left unanswered principally because of the scanty strain data taken below the vessel's neutral axis. In 1930 two identical 310-ft. transversely framed U.S. destroyers, "Preston" and "Bruce," [15,17] were observed while being loaded in sagging and hogging respectively. Within the past three years another British destroyer, the 355-ft. longitudinally framed "Albuera" [48] was similarly loaded in hogging. These vessels were of riveted construction and were loaded by being supported on piers in drydock as the water level and internal weight distribution were varied. The "Preston," "Bruce" and "Albuera" were loaded to destruction when complete buckling of deck or bottom structure occurred.

Except on the "Wolf," for which only fore and aft strains were measured, multiaxial plane strains were determined enabling principal stresses in magnitude and direction to be calculated. In all these cases, stress distribution was found to be in generally good agreement with classical beam theory even for extended ranges of loading.

Transversely framed, dry cargo or passenger type vessels of more than one deck have also been similarly studied by imposing known bending moments up to substantial magnitudes by adding and shifting weights while the ships were afloat in still water. Tankers, with their fine internal subdivision simplifying ballast shifting arrangements are ideal for such experiments, and several of them have been so investigated.

The results obtained to date indicate that generally good agreement exists between stresses calculated from measured strains and the stresses predicted by beam theory. This appears to be true even though the vessel has one or many full-width decks; whether it has corrugated, plane, or no longitudinal bulkheads; whether it is transversely, longitudinally or combinationally framed; or whether it is riveted or welded.

An interesting series of similar static tests have been performed by the British on identical cargo ships, "Ocean Vulcan" [43] and "Clan Alpine" [44] and on identical tankers, "Neverita" [36,37] and "Newcombia." [38,39] One vessel in each pair was riveted while the other was predominantly all welded. The purpose was to determine if there were any differences in structural response that might be attributed to the method of construction. As in other tests, good agreement was found between stresses computed from measured strains and those predicted from measured strains and those predicted from beam theory. In these investigations, however, more detailed strain measurements were made permitting an assessment of localized stresses. These results indicate that in specific areas there are discrepancies in the mid-thickness plate stresses (which will be discussed later).

For numerous cases, calculated and observed ship deflections were in good agreement and, once more, in the "Neverita"-"Newcombia" and "Ocean Vulcan"-"Clan Alpine" the differences, while possibly real, were nevertheless small. In fact, it may be concluded that the service deflections of ships built to existing standards of scantlings and frame spacing may be quite accurately predicted from calculations involving known bending moments and shearing forces by assuming all longitudinally continuous material fully effective, using the usual value of Young's modulus and taking into account shear deflections and insuring that thermal effects are minimized.

With the exception of the "Ocean Vulcan"-"Clan Alpine," no static tests appear to have been made of vessels in other than the upright position.

EFFECTS OF INITIAL UNFAIRNESS OF PLATING

Taking note of the aforementioned small deflection differences of the four British vessels suggests the following comments. Between the longitudinally framed ships, the difference in hull deflections was hardly large enough to be significant or within the range of experimental precision although it was slightly larger in the riveted ship. On the other hand, in the transversely framed ships even though some corresponding, localized rivet slip may have occurred in the riveted ship, the greater deflection was found in the welded ship. This may have been due to the initially greater panel unfairness in the transversely framed welded ship. That such panel unfairness did exist was borne out by careful surveys.

Furthermore, the observed deflection of even the transversely framed *riveted* ship exceeded the observed deflections of both longitudinally framed ships. Conceivably this could be laid to the greater unfairness of transversely framed pair (the welded one in particular) as opposed to the longitudinally framed pair.

As an example of the possible magnitude of such initial plate unfairness, in one panel of the "Philip Schuyler" it was observed to be 0.31 inches.[31,32]

Earlier studies have also attributed greater-than-expected hull deflections to initially unfair plating. Increasing hogging bending moments in the "Cuyama," [16] caused an apparent increase in the vessel's stiffness. This was possibly due to the known initially unfair deck plating rather than to rivet slip particularly in view of the moderate magnitude of the loads imposed and the increasing evidence from other tests that rivet slip plays no significant part.

Nevertheless, ship deflection is not the primary aspect of the matter. Should local plating unfairness be appreciable, the curved fibers of the plating will not carry their predicted magnitudes of either tensile or compressive load. Naval architects have probably been more aware of the reduced load carrying capacity of initially bowed plating in compression than they have been in tension. For increasing tensile loading in plating with initial curvature, the unfairness must, of course, decrease and more of the material take its full share of load. However, if the initial unfairness is beyond some limiting value, even large ship bending moments will not be sufficient to substantially strain the mid panel—midthickness fibers although at the surface the bending stresses may easily be three times the midthickness stress. Disproportionately

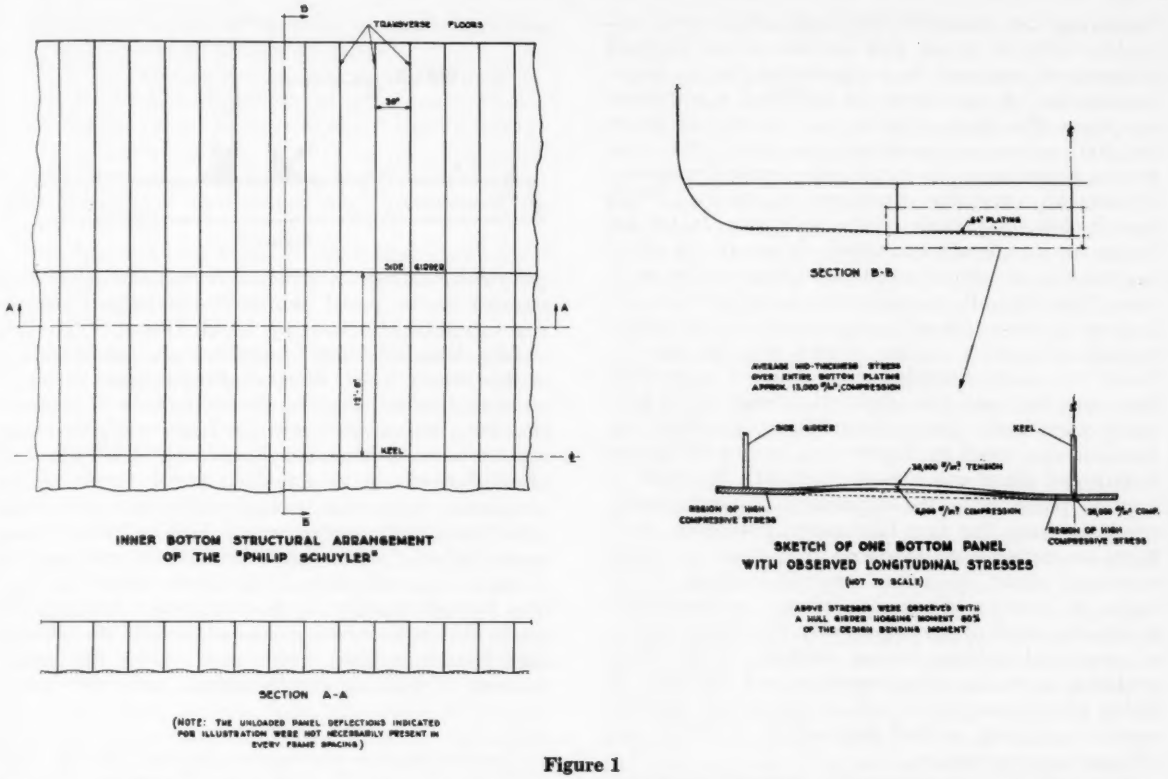

TRANSVERSE FLOORS
KEEL
INNER BOTTOM STRUCTURAL ARRANGEMENT OF THE "PHILIP SCHUYLER"
SECTION A-A
(NOTE: THE UNLOADED PANEL DEFLECTIONS INDICATED FOR ILLUSTRATION WERE NOT NECESSARILY PRESENT IN EVERY FRAME SPACING)
SECTION B-B
SIDE GIRDER
KEEL
REGION OF HIGH COMPRESSIVE STRESS
SKETCH OF ONE BOTTOM PANEL WITH OBSERVED LONGITUDINAL STRESSES
(NOT TO SCALE)
ABOVE STRESSES WERE OBSERVED WITH A HULL GIRDER HOGGING MOMENT 80% OF THE DESIGN BENDING MOMENT

Figure 1

high stresses, substantially constant through the plate thickness, would then be the rule at the longitudinal stiffening members. These high stresses or those at the plating surface due to bending, may conceivably contribute to cracking, especially in the presence of load alternations, which may be augmented by shock loadings due to slamming and/or residual welding stresses. (Figure 1). In fact, superficial fissures in the plating along the panel boundaries are reported by Murray in Reference 60. (Between differing degrees of initial bulging there may be in one a greater tendency for crack initiation but a lesser tendency for crack propagation while in another the reverse may be the case under the variable ship bending moment.) It is worthy of note that bottom plating strain measurements, especially in the "Ocean Vulcan"-"Clan Alpine" comparison, point out the larger local fluctuations from beam theory stresses in the welded ship for both hogging and sagging. (Figure 2). This substantiates the foregoing argument since the initial plate unfairnesses of the welded ship were generally about twice those of the riveted ship. Based upon such measurements and practical observations, these differences in plating unfairness are considered typical for the two methods of fabrication, at least as of the war-built ships.

Thus, it appears, that in addition to the factors generally considered as contributing to the less satisfactory structural performance of the welded ships of wartime construction versus riveted ships, there may well be the added factor of initially unfair plating.

To date, there is still room for suspicion that the whole explanation for the difference in structural performance between riveted and welded ships has not been found. This is an all-important question, and it cannot be satisfactorily explained by laying blame entirely on the steel, the welding workmanship or the design details. Presumably the condition for brittle fracture in steel may consist of several components

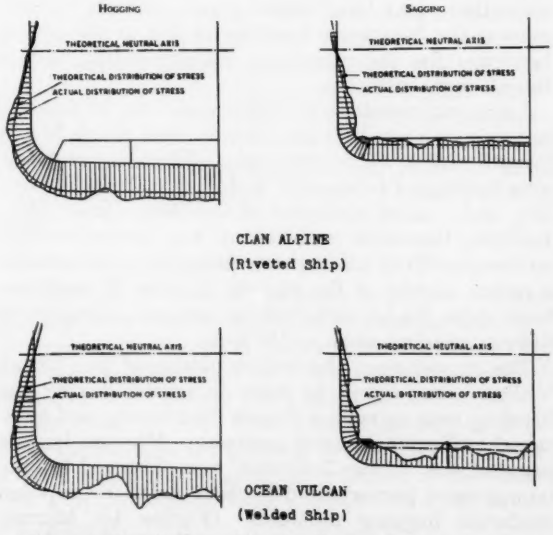


Figure 2. Distribution of longitudinal mid thickness stresses for bottom shell plating near amidships.

including low temperature, high strain rate, and multiaxiality of stress. The absence of one or small amounts of one may be compensated for by larger magnitudes of the others in fulfilling a minimum condition. The effect of unfairness not only enhances the static stress in a localized area, but by the same means it increases the strain rate under the strictly dynamically variable conditions of reality. While the absolute magnitude of the unfairness factor has yet to be completely evaluated, as one of the above ingredients, its importance is out of proportion to its size. Even if small, it could serve to explain the difference in structural performance not only between a welded ship and a similar riveted ship but also between two similar welded ships since it is probable that even between two identical, welded ships built under apparently identical conditions significant differences can exist in degree and extent of plating unfairness. Emphasis should therefore be made to explain more fully the difference in performance resulting from the two fabrication processes, since there is certainly no evidence that these processes have any effect upon the external loadings of the ships. A broader, more satisfactory understanding is also required of the apparently capricious nature of structural failures among welded vessels. More evidence as to the characteristics and behavior of unfair plating may contribute to the present hypotheses in explaining welded ship failures and their discriminating occurrence.

That welded plating generally requires more care and remedial treatment than riveted is reasonable and well known and is due to thermal distortions accompanying the welding process. These then may occur on account of welding at seams and butts of plating and in way of the plating—stiffener connections through closing up of the angle including the fillet weld and axial contraction along it. (Figure 3).

What is the allowable limit of unloaded plating unfairness? The limit, which insures against crack formation at the longitudinal panel supports (or perhaps at the transverse boundaries due to plate panel bending) for the maximum loading antipicated, is the ultimate criterion.

Large unloaded panel deflections may be attained not only as a result of construction techniques but by growth under water pressure and hogging and sagging loadings. Professor H. E. Jaeger of Delft Universitv, and a panel chairman of the Netherlands Shipbuilding Research Association, has presented data on the growth of plating unfairness as an outcome of a recent survey of the plating of some 36 wartime-built ships. He has observed permanent plating panel deflections of as much as 1¼ inch.

The curvature of the bottom plating of the "Ocean Vulcan" was found to have increased during the bending tests to such a degree that fairing and additional stiffening became necessary. Previously, one panel of the "Philip Schuyler" was observed to take on increased permanent deflection under the imposed moderate hogging moments. (Figure 4.) Murray (Reference 60) has experimentally confirmed the

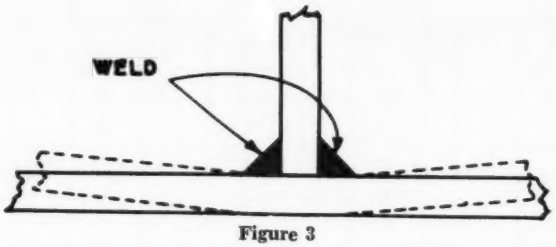
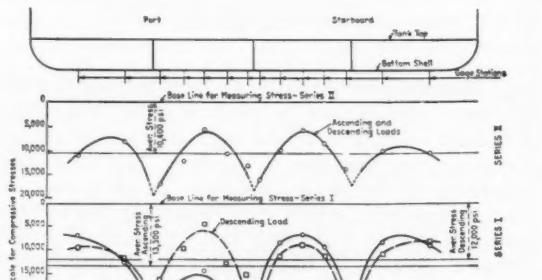


Figure 3

growth of plating unfairness and the presence of high stresses at the panel boundaries of bulged plating. An unpublished report by M. R. Horne of the Admiralty Ship Welding Committee and an extension of this theory by H. Bleich, taking account of initial residual stresses, explain the occurrence of progressive buckling at relatively low loads and give an insight into its mechanism. According to Bleich, progressive buckling in a welded panel would be accompanied by a reduction of residual stresses. Such a compensating reaction would lead to little, if any, stress increase at the panel boundaries with growth of unfairness and seems to mitigate the brittle fracture hazard accountable to progressive bulging. No doubt, this is fortunate since Jaeger is of the opinion that plastic bulging may occur when the initial amount of built-in constructional unfairness is as



Longitudinal Membrane Stresses for Hog Moment of 134,000 Foot-Tons

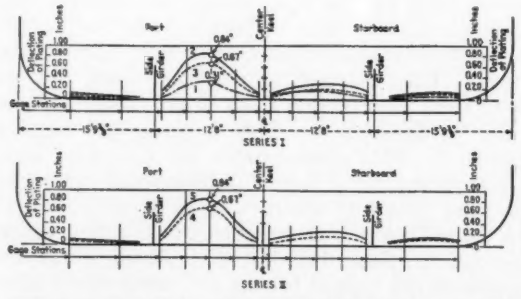


Figure 4. (1) Initial position of bottom plating. (2) Position under first hogging moment of 134,000 ft. tons. (3) Position on return to 20,000 ft. tons. (4) Position under 20,000 ft. tons. (5) Position under second hogging moment of 134,000 ft. tons. Deflection Profile of Bottom Plating Midway Between Two Frames Amidships. Bottom Plating Behavior on the "Philip Schuyler."

small as 1/6 the plating thickness (presumably when adjacent fore and aft panels are plane).

There yet remains for consideration the stress situation in panels with degrees of unfairness as fabricated which have not encountered the alleviating effect of increasing bulging with service. The boundary stresses will then be superimposed on the residual stresses and their magnitude is therefore of interest.

Two series of investigations have been carried out to examine this factor at M.I.T. These served as the theses for Haskell, Wurlitzer, Freire and Winkelmann. Each model was welded of mild steel and was stress relieved. It was approximately representative of three longitudinally adjacent panels of a transversely framed ship's deck or bottom. The panel side ratio was 3 to 1 and the width-thickness ratio, 48. The only difference between models was in the amount of initial unfairness. Maximum deflections were 0", ⅛", 3/16", and one of twice the plate thickness, i.e., ¼". Only the center panel in each case had this set, the others being substantially plane. Characteristics of panels and stiffening members were chosen to represent a typical transversely framed ship. Broadly speaking and within the elastic range, the ratio of maximum mid thickness local strain (i.e., at longitudinal boundaries) / average strain increases linearly with the ratio maximum initial deflection/plate thickness. When the deflection ratio is unity, the maximum mid thickness stress at the stiffener is about 20-25% greater than the uniform stress in an identical plane panel. This should be taken as indicating merely an order of magnitude and nothing exact. With a larger panel aspect ratio, this augment should be larger whereas for several panels of width, only some of which are initially bowed, the augment of local over average stress should be smaller.

Unfairness in the ship's compression flange, if severe and extensive enough, will decrease the section modulus even in the tension flange and so may raise the stress there in fair plating. Unfairness of bottom plating will conceivably increase the stress level in the deck by 3-5%. Unfairness in both tension and compression areas naturally compounds the evils. The report of the Board of Investigation to Inquire into the Design and Methods of Construction of Welded Steel Merchant Vessels in 1946 stated that buckles were involved in very few of the casualties and, in no case, were they considered responsible for endangering the vessel, and were hence not analyzed in the report. On the other hand, Dr. G. Vedeler, Managing Director of the Norwegian Bureau Veritas, in a recent article,[57] suggests the possibility of buckling of the deck contributing to, if not causing, the failure of six transversely framed tankers which broke in two, not by brittle fracture, but by tearing in the bottom plates. It is not reported whether the ships were of welded or riveted construction, yet the implication is clear that ships may break up in a variety of ways and for diverse reasons. Here too, however, it is not unreasonable to suspect unfair plating as an extenuating contributor to structural disaster.

It may be argued that the eccentricity of loading at a riveted shell butt lap is an equally serious condition which has not proven critical. However, reflection will show that such eccentricity while causing some stress variations through the thickness of the plating nevertheless does not raise the over-all stress level in the plate. It is to be noted that in way of riveted butt laps, stiffness of the panel is increased with consequently less panel unfairness. Furthermore, the effect of the eccentricity is limited in extent to no more than about 25% of the plating in a girthwise direction between two frames because of the required staggering of riveted butts.

Although offering a smaller statistical sample, satisfactory performance of ships built since 1945 gives reason for optimism.[59] This apparent improvement may be due to the returned pride of craft and skill resulting in improved ship fitting and, therefore, less unfair plating. In addition, more suitable materials have been specified and greater vigilance of welded construction is exercised in design and fabrication.

The ultimate answers to be sought, if unfair plating is indeed a critical factor in the problem of welded ship failures, as seems likely, should settle the questions of how much initial deflection is admissable to limit stress. Performing the major portions of all seam and butt welds from the inside surface of the shell so as to set up an initial panel bulge in opposition to the water pressure load, and providing greater width of landing than the mere web thickness of the stiffener to back up the plating may be effective remedies. Turnbull [49] and others have advocated longitudinal framing in preference to transverse for the deck and bottom stiffening. Substituting intermittent welding for continuous in the shell frame connection may be considered. Indeed it appears highly desirable that initial unfairness in the skin of the ship be limited by whatever means practicable. It may well be that ships over about 700 feet in length, because of their thicker plating, may not be as subject to critical bulging. At the other extreme, small vessels, despite their thin plating and consequent disposition toward washboarding, may not suffer since for those under about 200 feet in length the shell thicknesses are based more upon lateral panel loadings than hogging and sagging loads which are comparatively small.

Applicability to Recent Structural Failures

In the light of recent past experience, it is evident that answers should be sought to explain not only differences in structural performance between riveted and welded ships but between *some welded ships and other welded ships* of the same design.

That stress or stress history are important in cases of brittle fracture is indicated by the high incidence of such failures originating in portions of the structure with the highest basic stress levels (viz., decks and bottom).

Unusually high basic stress at time of fracture is

probably not required as seen from those cases known to have occurred when levels of nominal, computed stress were only moderate.

Evidence of past high stress levels would be exhibited in plastic deformation and/or macroscopic cracks which may have characteristics sufficient to initiate brittle fracture under conditions of low temperature.

Plating unfairness bringing about a reduction in ship section modulus and a peaking of stress is generally larger in welded than in riveted ships. Furthermore, it is sufficiently variable from ship to ship and from panel to panel to encompass many shades of difference in structural performance between welded ships of the same class.

The improved structural performance of welded Liberty ships with improved details,[59] permitting them to be compared favorable with partially riveted Liberty ships may simply indicate that no one or two factors alone but several are necessary to initiate brittle fracture. The elimination of one such factor, in the form of improvements to hatch-corner design details, for example, may have been sufficient to reduce the likelihood of structural distress to a tolerable limit in the all welded ships. (Nevertheless, the stresses in localized areas of welded ships may still have been in excess of those in similar locations of riveted vessels, presuming the riveted ships to have been conservatively stressed as was apparently the case.)

By far, the highest incidence of fracturing in the Liberty ships occurred at the hatches or the vessel's sides in the neighborhood of the Upper Deck, amidships.[59] Hazarding a reconstruction of a typical failure on the basis of the foregoing results in the following illustration.

The largest standard, calculated values of ship bending moment take place when the vessel is at, or near, its full load condition. For vessels with machinery amidships, as in the Liberty ships, the greater moment occurs almost invariably under the hogging condition which puts the deck in tension and the bottom in compression.

Any unfair bottom plating would reduce somewhat the section modulus and thus increase slightly the general stress level even in the upper deck.

Panels of deck plating are bounded by the transverse deckbeams and, in the direction of the tensile stress, by the vessels sides and hatch side girders. The cumulative effect of high stress peaks at side and hatch due to deck plating unfairness being augmented locally by residual welding stresses and in the presence of a sharp discontinuity, such as a hatch corner or sheer strake cut-out, may be sufficient to initiate a crack. This crack, under auspicious conditions of temperature and loading, may subsequently spread in the characteristically brittle manner.

It may be significant that vessels similar to the Libertys but with an additional longitudinal stiffening member supporting the main deck panels between the hatch coaming and the ship's side (thus limiting panel unfairness) apparently suffered less from brittle fracture troubles.

If, in the upper side shell area, the panel dimension in the direction of the tensile stress is subject to greater increase for a bowed panel than for a plane one, under equal loads, then the deck stresses in a ship with such bowed panels would very likely be larger than those of a second ship with plane side shell panels. The second ship here is meant to typify the Bethlehem-Fairfield group of Liberty ships with riveted shell seams. These may be expected to have had fairer plating and an effectively reduced panel dimension because of the lapped joints. Bottom plating of these riveted ships should likewise be more effective. The panels should also have greater shear carrying capacity from the instability aspect because of the smaller effective panel dimension.

In tankers, the distribution of cargo is subject to such wide variations that equally large hogging and sagging bending moments are possible. Unfairness of plating in these normally longitudinally framed ships is not as great as in those transversely framed. Nevertheless, this condition may conceivably add a share of stress concentration to that existing at such structural discontinuities as bilge keels and at ends of longitudinals at transverse bulkheads in T-2 tankers.

On the other hand, since plating unfairness is apparently less a factor in longitudinally framed ships than in those transversely framed, it seems not unlikely that riveted crack arrestors will prove less beneficial in T-2 tankers than in Liberty ships for example. The implication here is that crack arrestors may have alleviated the occurrence of brittle fracture largely through fairing the plating and thereby reducing stress augmentation.

While the contribution of unfair plating may be, by itself, a relatively small one and important only in combination with others, it nonetheless may be the "last straw" and serve to initiate trouble in one structure whereas another, apparently identical, is free of it. Establishment of a maximum tolerable value of fabrication unfairness seems indicated in order for the designers to know more precisely the latitude within which his decisions must be made. Judging from the present, sharply reduced incidence of fracture, any reasonable standard may now be attainable a priori. In those panels not meeting the standard, excesses of built-in deflection should be easy to detect and corrected by light panel reinforcement, perhaps, when occurring in an area of high nominal tensile stress. The same levels of basic ship girder stress now permitted may then be continued with more confidence or reexamined with fuller knowledge.

As a very tentative limit of fabrication unfairness for transversely oriented plating panels, one half the thickness may be in order for transversely isolated panels, others being substantially plane. A limit of about one quarter the thickness may be acceptable for unfairness which is more generally prevalent in a transverse plane. Since both these limits are greater than the 1/6 thickness of Jaeger, the adjacent panels forward and aft of the ones in question are, by implication, also assumed to be sufficiently unfair so that

additional bulging and stress relief in service is unlikely in the central panel. Initially unfair panels isolated or unique longitudinally may not be sources of trouble except during the early life of the ship in panels whose initial unfairness exceeds the plating thickness.

ACKNOWLEDGEMENT

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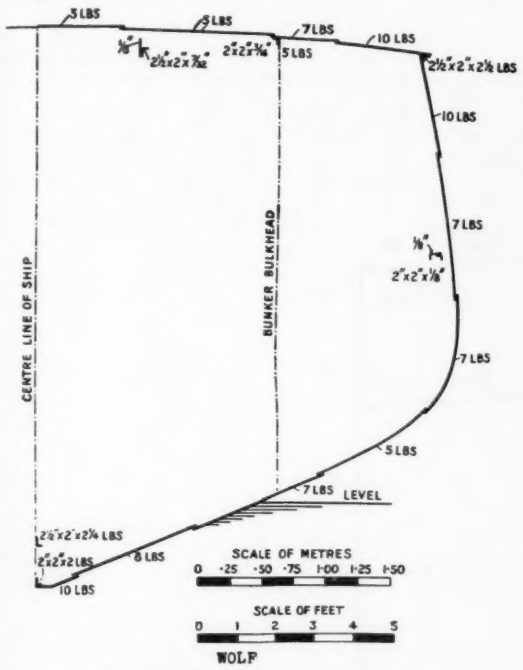
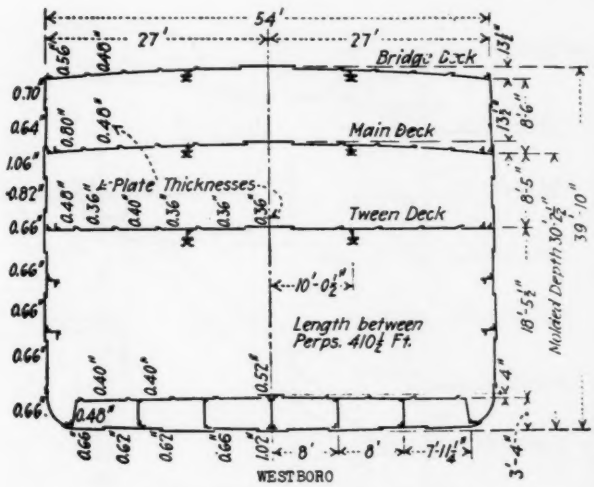


Longitudinally continuous material



Longitudinally continuous material

Figure 5

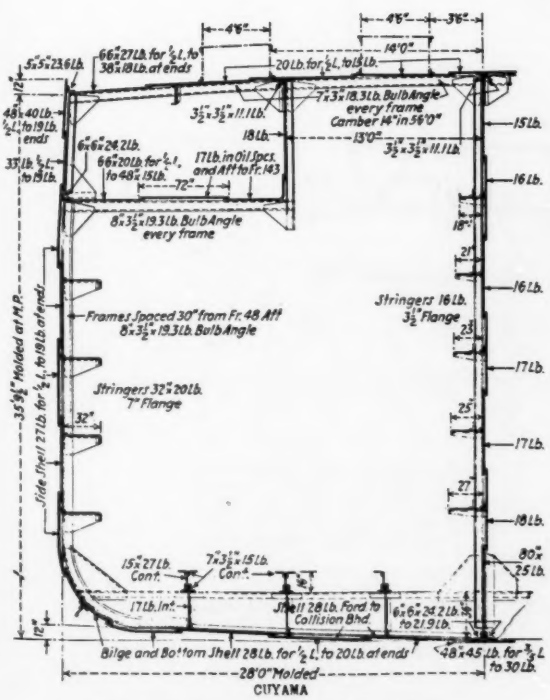

Frames Spaced 30" from Fr. 48 Aft
8"x3½"x19.3 Lb. Bulb Angle
Stringers 16 Lb. 3½" Flange
Stringers 32"x20 Lb. 7" Flange
Shell 28 Lb. Ford to Collision Bhd.
Bilge and Bottom Shell 28 Lb. for ½ L. to 20 Lb. at ends
28'0" Moulded
CUYAMA

Figure 6. "Cuyama." Midship Section.

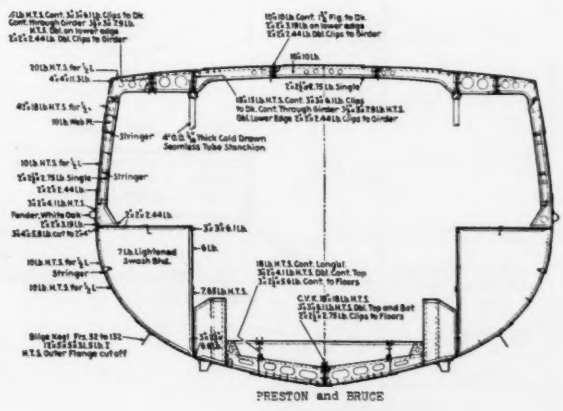
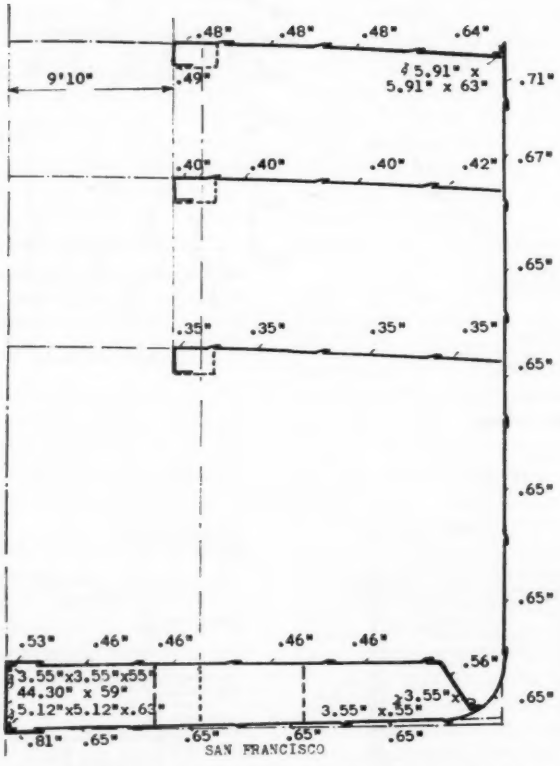
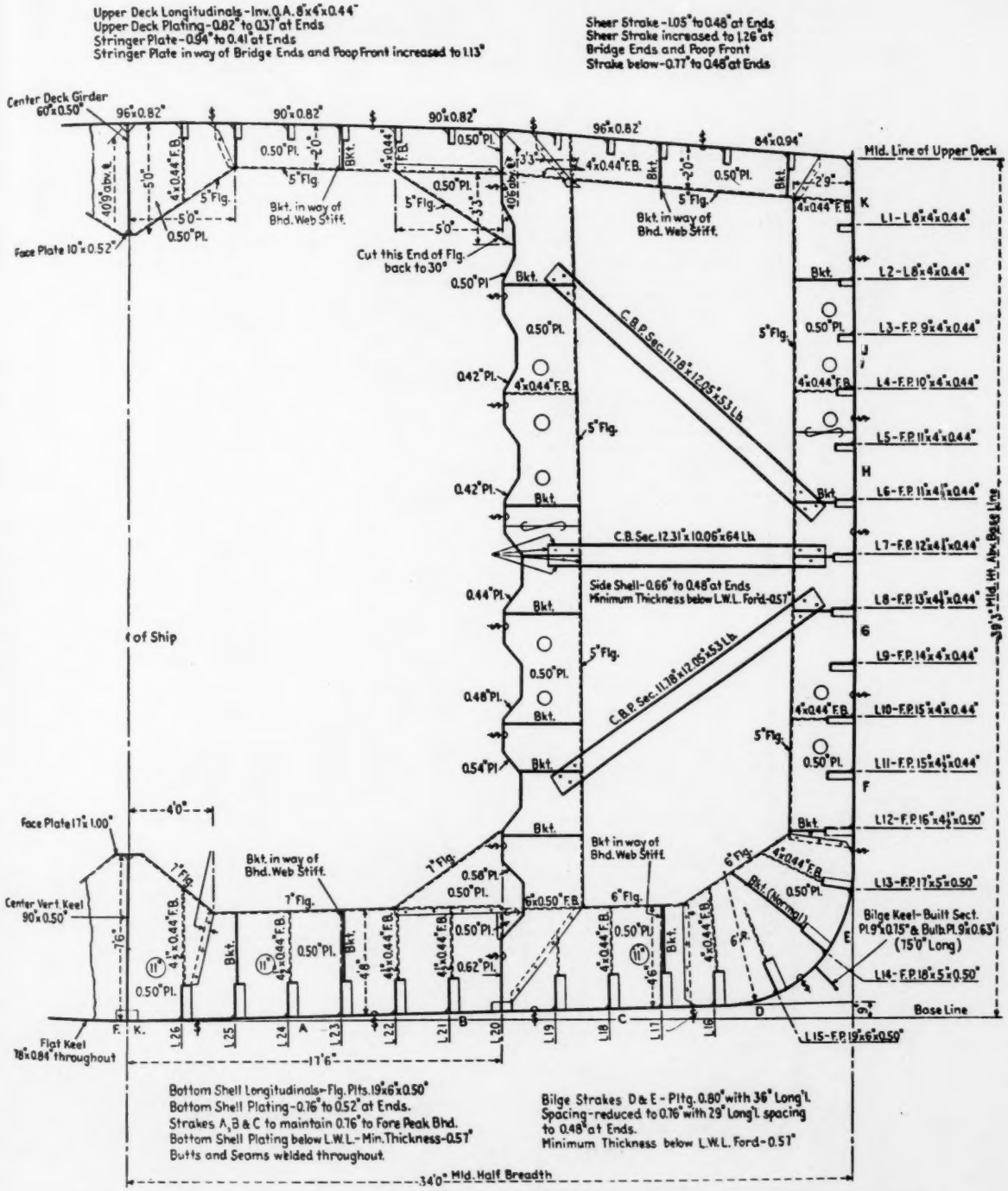


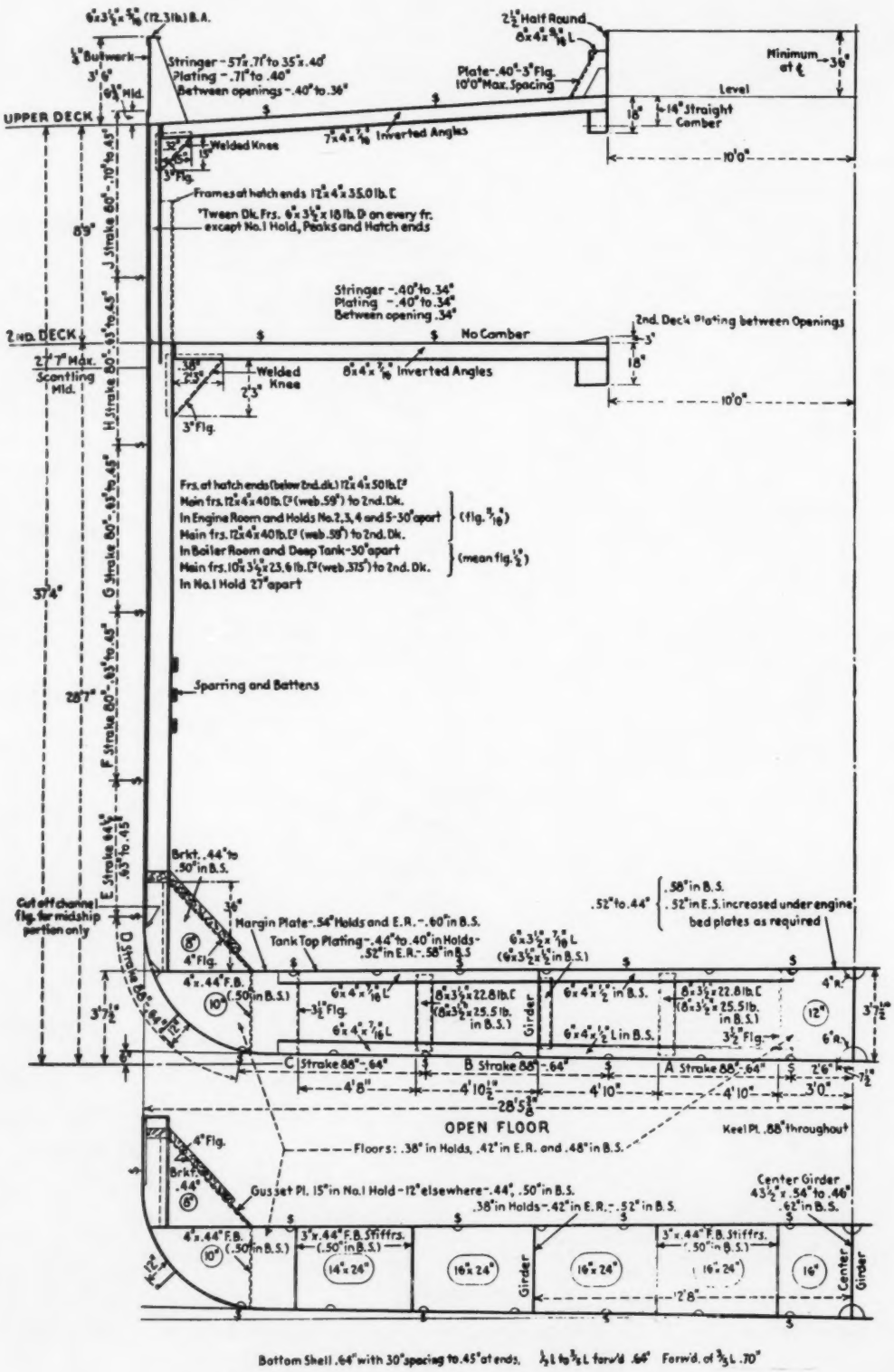
Figure 7. "Preston" and "Bruce." Midship Section.



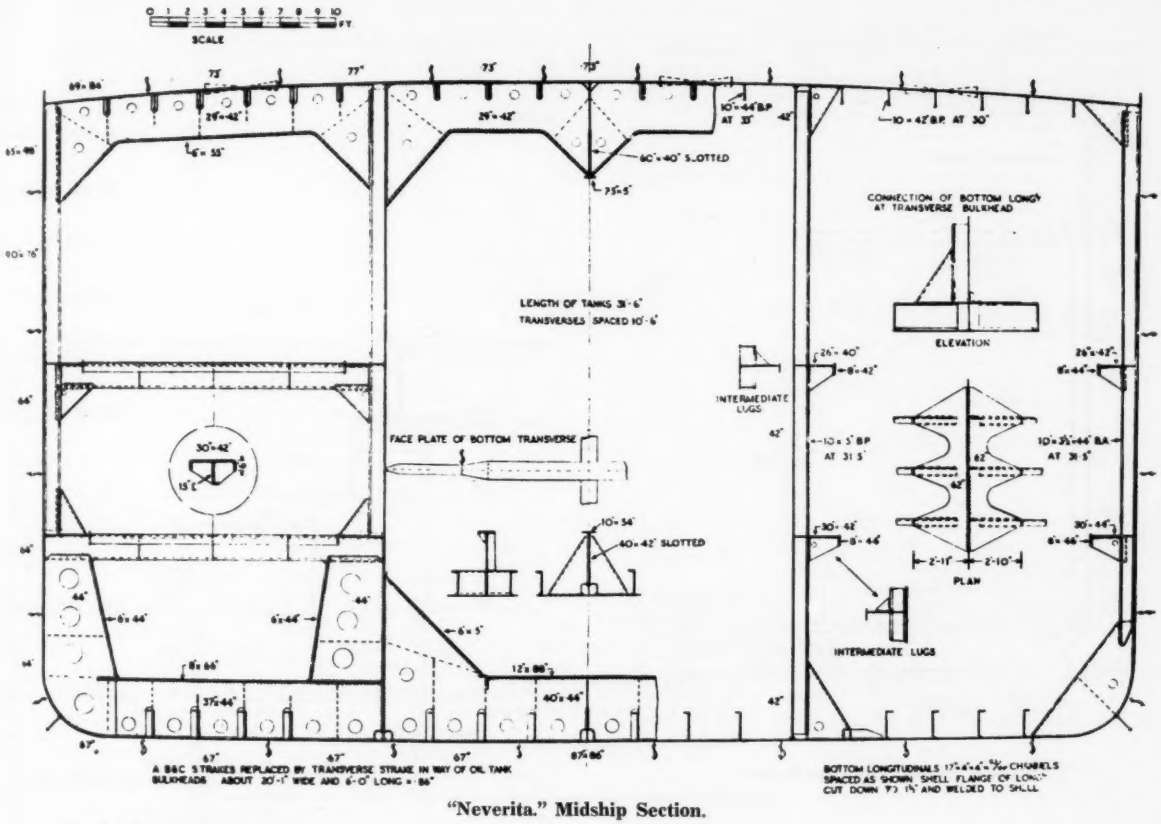
"San Francisco." Longitudinally continuous material (Reference 17).


Upper Deck Longitudinals - Inv. Q.A. 8"x4"x0.44"
Upper Deck Plating - 0.82" to 0.31" at Ends
Stringer Plate - 0.94" to 0.41" at Ends
Stringer Plate in way of Bridge Ends and Poop Front increased to 1.13"
Sheer Strake - 1.05" to 0.48" at Ends
Sheer Strake increased to 1.26" at Bridge Ends and Poop Front
Strake below - 0.77" to 0.48" at Ends
Mld. Line of Upper Deck
Center Deck Girder 60"x0.50"
Face Plate 10"x0.52"
C.B.P. Sec. 11.78"x12.05"x53 Lb.
C.B. Sec. 12.31"x10.06"x64 Lb.
Side Shell - 0.66" to 0.48" at Ends
Minimum Thickness below L.W.L. Ford - 0.57"
℄ of Ship
Bkt. in way of Bhd. Web Stiff.
Cut this End of Flg. back to 30°
L1 - L8"x4"x0.44"
L2 - L8"x4"x0.44"
L3 - F.P. 9"x4"x0.44"
L4 - F.P. 10"x4"x0.44"
L5 - F.P. 11"x4"x0.44"
L6 - F.P. 11"x4½"x0.44"
L7 - F.P. 12"x4½"x0.44"
L8 - F.P. 13"x4½"x0.44"
L9 - F.P. 14"x4"x0.44"
L10 - F.P. 15"x4"x0.44"
L11 - F.P. 15"x4½"x0.44"
L12 - F.P. 16"x4½"x0.50"
L13 - F.P. 17"x5"x0.50"
L14 - F.P. 18"x5"x0.50"
L15 - F.P. 19"x6"x0.50"
Bilge Keel - Built Sect. Pl. 9"x0.75" & Bulb Pl. 9"x0.63" (75'0" Long)
Face Plate 17"x1.00"
Center Vert. Keel 90"x0.50"
Flat Keel 78"x0.84" throughout
Base Line
39'3" Mld. Ht. Abv. Base Line
34'0" Mld. Half Breadth
Bottom Shell Longitudinals - Flg. Pts. 19"x6"x0.50"
Bottom Shell Plating - 0.76" to 0.52" at Ends.
Strakes A, B & C to maintain 0.76" to Fore Peak Bhd.
Bottom Shell Plating below L.W.L. - Min. Thickness - 0.57"
Butts and Seams welded throughout.
Bilge Strakes D & E - Pltg. 0.80" with 36" Long'l. Spacing - reduced to 0.76" with 29" Long'l. spacing to 0.48" at Ends.
Minimum Thickness below L.W.L. Ford - 0.57"

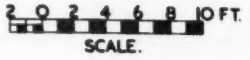
T2 tanker midship section similar to "Shiloh," "Elk Hills," "Ventura Hills," "Antelope Hills," "Fort Mifflin."

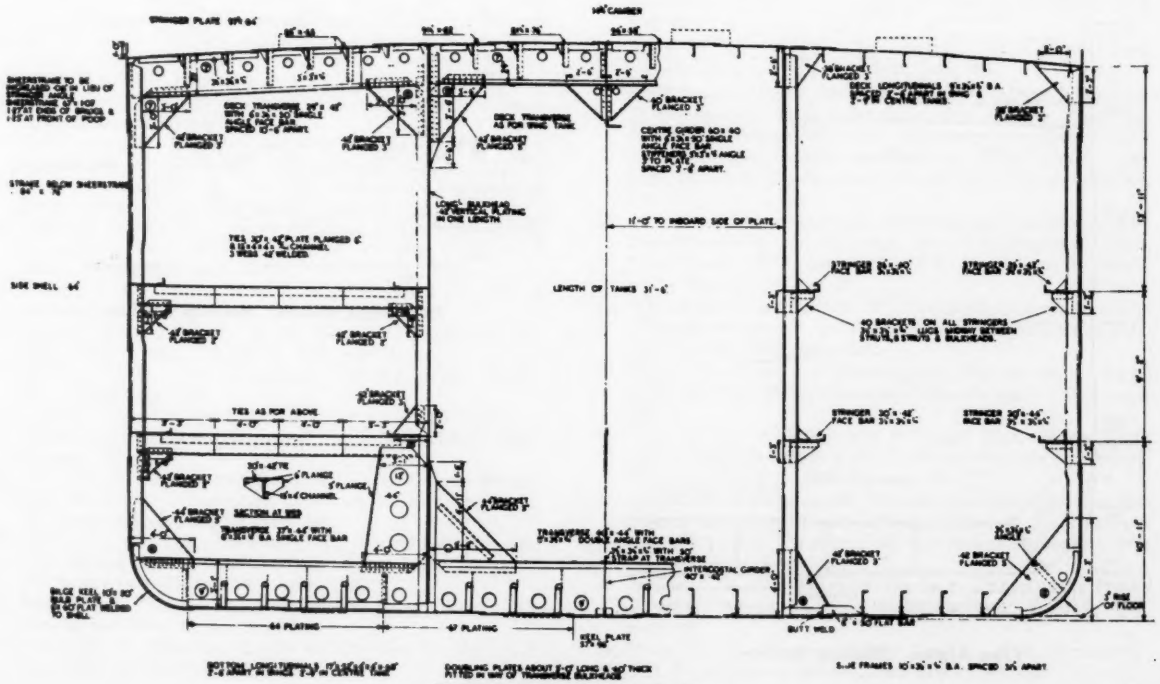

UPPER DECK
2nd. DECK
Stringer - 57½".71 to 35".40
Plating - .71" to .40"
Between openings - .40" to .36"
2½" Half Round
Plate - .40" - 3" Flg.
10'0" Max. Spacing
Minimum at ℄ 36"
Level
14" Straight Camber
Welded Knee
Inverted Angles
10'0"
Frames at hatch ends 12"x4"x35.0 lb. [
"Tween Dk. Frs. 6"x3½"x 18 lb. D on every fr. except No. 1 Hold, Peaks and Hatch ends
Stringer - .40" to .34"
Plating - .40" to .34"
Between opening .34"
No Camber
2nd. Deck Plating between Openings
Scantling Mld.
Frs. at hatch ends (below 2nd. dk.) 12"x4"x 50 lb. [
Main frs. 12"x4"x 40 lb. [(web .59") to 2nd. Dk.
In Engine Room and Holds No. 2, 3, 4 and 5 - 30" apart
Main frs. 12"x4"x 40 lb. [(web .59") to 2nd. Dk.
In Boiler Room and Deep Tank - 30" apart
Main frs. 10"x3½"x 23.6 lb. [(web .375") to 2nd. Dk.
In No. 1 Hold 27" apart
Sparring and Battens
Brkt. .44" to .50" in B.S.
Margin Plate - .54" Holds and E.R. - .60" in B.S.
Tank Top Plating - .44" to .40" in Holds - .52" in E.R. - .58" in B.S.
.52" to .44"
.58" in B.S.
.52" in E.S. increased under engine bed plates as required
Cut off chaining flg. for midship portion only
Girder
C Strake 88" - .64"
B Strake 88" - .64"
A Strake 88" - .64"
OPEN FLOOR
Keel Pl. .88" throughout
Floors: .38" in Holds, .42" in E.R. and .48" in B.S.
Gusset Pl. 15" in No. 1 Hold - 12" elsewhere - .44", .50" in B.S.
.38" in Holds - .42" in E.R. - .52" in B.S.
Center Girder 43½" x .54" to .46" .62" in B.S.
Bottom Shell .64" with 30" spacing to .45" at ends. ½ L to ⅗ L forw'd .66" Forw'd. of ⅗ L .70"

Liberty ship midship section similar to "Philip Schuyler."

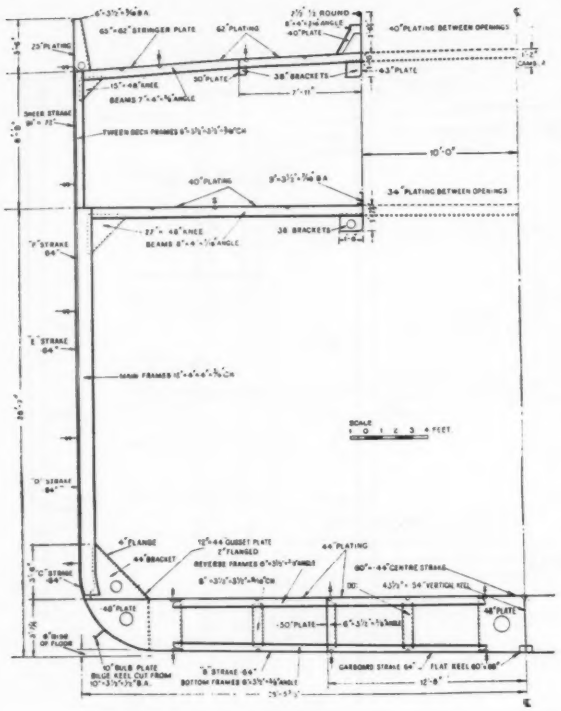

SCALE
LENGTH OF TANKS 31'-6"
TRANSVERSES SPACED 10'-6"
FACE PLATE OF BOTTOM TRANSVERSE
INTERMEDIATE LUGS
CONNECTION OF BOTTOM LONG'S AT TRANSVERSE BULKHEAD
ELEVATION
PLAN
INTERMEDIATE LUGS
A B&C STRAKES REPLACED BY TRANSVERSE STRAKE IN WAY OF OIL TANK BULKHEADS ABOUT 20'-1" WIDE AND 6'-0" LONG = 86"
BOTTOM LONGITUDINALS

"Neverita." Midship Section.

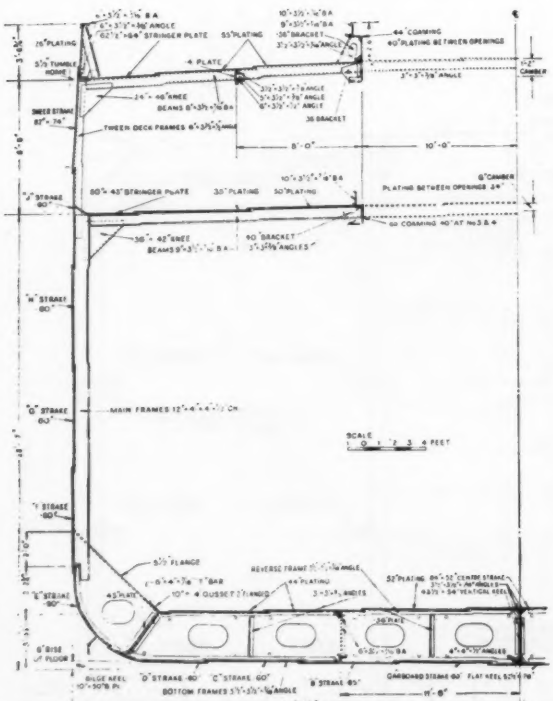




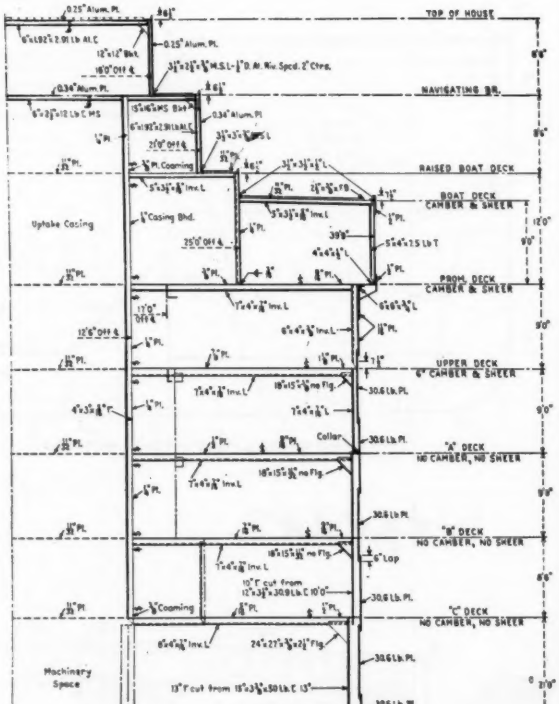
"Newcombia." Midship Section.



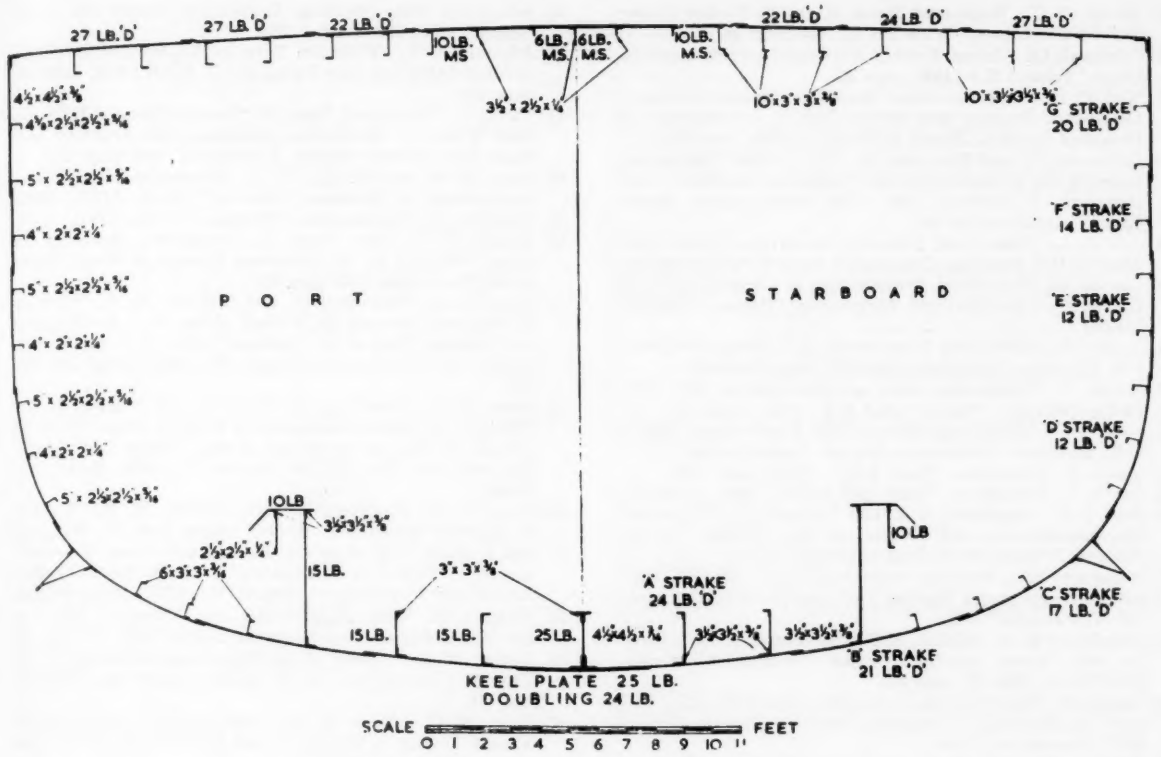
"Ocean Vulcan." Midship Section.



"Clan Alpine." Midship Section.



"President Wilson." Midship Section.


27 LB. 'D'
27 LB. 'D'
22 LB. 'D'
10LB. M.S.
6LB. M.S.
6LB. M.S.
10LB. M.S.
22 LB. 'D'
24 LB. 'D'
27 LB. 'D'
4½ x 4½ x ⅜"
4½ x 2½ x 2½ x ¾"
5" x 2½ x 2½ x ⅜"
4" x 2" x 2" x ¼"
5" x 2½ x 2½ x ⅜"
4" x 2" x 2" x ¼"
5" x 2½ x 2½ x ⅜"
4" x 2" x 2" x ¼"
5" x 2½ x 2½ x ⅜"
3½ x 2½ x ¼"
10" x 3" x 3" x ⅜"
10" x 3½ x 3½ x ⅜"
'G' STRAKE 20 LB. 'D'
'F' STRAKE 14 LB. 'D'
'E' STRAKE 12 LB. 'D'
'D' STRAKE 12 LB. 'D'
'C' STRAKE 17 LB. 'D'
'B' STRAKE 21 LB. 'D'
'A' STRAKE 24 LB. 'D'
PORT
STARBOARD
10LB
3½ x 3½ x ⅜"
2½ x 2½ x ¼"
6" x 3" x 3" x ⅜"
15LB.
3" x 3" x ⅜"
15LB.
15LB.
25LB.
4½ x 4½ x ⅜"
3½ x 3½ x ⅜"
3½ x 3½ x ⅜"
10LB
KEEL PLATE 25 LB.
DOUBLING 24 LB.
SCALE
FEET
0 1 2 3 4 5 6 7 8 9 10 11

"Albuera." Longitudinally continuous material.

BIBLIOGRAPHY

1. Biles, J. H., "The Strength of Ships with Special Reference to Experiments and Calculations Made Upon *H.M.S. Wolf*," Trans. I.N.A., 1905, page 80.
2. Howard, J. E., "Strains in the Hull of a Ship at Sea, and Those Measured While Receiving Cargo," Trans. S.N.A.M.E., 1913, page 119.
3. Smith, S. F., "Change of Shape of Recent Colliers," Trans. S.N.A.M.E., 1913, page 145.
4. Cornbrooks, T. M., "Data on Hog and Sag of Merchant Vessels," Trans. S.N.A.M.E., 1915, page 141.
5. ————, "New Data on Ship Stresses," Engineering News-Record, September 18, 1919, page 550.
6. Hoffman, G. H., "Analysis of Sir John Bile's Experiments on *H.M.S. Wolf*, in the Light of Pietzker's Theory," Trans. I.N.A., 1925, page 41.
7. Taylor, J. L., "Some Ship Strain Observations with a Simple Instrument," Trans. I.N.A., 1926, page 257.
8. Burtner, E. and Tingey, R. H., "Car Float Strength and Deflection," Trans. S.N.A.M.E., 1927, page 1.
9. Hoffman, G. H., "The Effective I of *H.M.S. Wolf*," Trans. I.N.A., 1928, page 153.
10. Laws, B. C., "The Behavior of a Cargo Vessel During a Winter North Atlantic Voyage," Trans. N.E.C.I.E.S., 1929–30, page 107.
11. Siemann, "Aufgaben und Fortschritte der Dehnungsmessung am Schiff im Seegang," Jahrbuch der Schiffbautechnischen Gesellschaft, 1929, page 148.
12. Dahlmann, W. and Henschke, W., "Durchfuhrung und Auswertung von Festigkeitsmessungen am Langsverband," Werft-Reederei-Hafen. 1931, page 109.
13. Roop, W. P., "Elastic Characteristics of Fleet Oilers," U.S. Exp. Model Basin Report No. 260.
14. Roop, W. P., "Bending Loads on Cuyama at Sea," U.S. Exp. Model Basin Report No. 297.
15. Kell, C. O., "Investigation of Structural Characteristics of Destroyers *Preston* and *Bruce*," Trans. S.N.A.M.E., 1931, page 35.
16. Roop, W. P., "Elastic Characteristics of a Naval Tank Vessel," Trans. S.N.A.M.E., 1932, page 314.
17. Schnadel, G., "Die Beanspruchung des Schiffes in Seegang. Dehnungs-und Durchbiegungsmessungen an Bord des *M.S. San Francisco* der Hamburg-Amerika Linie," Jahrbuch der Schiffbautechnischen Gesellschaft, 1936, page 129 (U.S. Experimental Model Basin Translation No. 11).
18. Horn, F., "Hochseemesfahrt. Schwingungs-und Beschleunigungsmessungen," Jahrbuch der Schiffbautechnischen Gesellschaft, 1936, page 153 (U.S. Experimental Model Basin Translation No. 26).
19. Weinblum, G. and Block, W., "Stereophotogrammetrische Wellenaufnahmen," Jahrbuch der Schiffbautechnischen Gesellschaft, 1936, page 214.
20. Weiss, G., "Gerat zur Messung der Wellenkontur," Jahrbuch der Schiffbautechnischen Gesellschaft," 1936, page 251.
21. Schnadel, G., "Shio Stresses in Rough Water in the Light of Investigations Made Upon the Motorship *San Francisco*," Trans. N.E.C.I.E.S., 1937–38, page 119.
22. Lienau, O., "Messungen uber das Arbeiten des Schiffsbodens und der Decksbeplattung Wahrund der Hochseemesfahrt, 1934," Jahrbuch der Schiffbautechnischen Gesellschaft, 1937, page 329.
23. Stocks, C. H., "Longitudinal Stress in Ships During Heavy Weather," Trans. Liverpool Engineering Society, 1937, page 87.
24. Roop, W. P., "Service Strain Tests of Hull Structures," U.S. Experimental Model Basin Report No. 467.

25. Bridge, I. C., "Structural Stress in an Oil Tanker Under Service Conditions," Trans. I.N.A., 1938, page 161.
26. Schnadel, G., "Ocean Waves," Freeboard and Strength of Ships," Trans. I.N.A., 1938, page 387.
27. Kell, C. O., "Investigation of Structural Characteristics of Destroyers *Preston* and *Bruce*, Part 2 — Analysis of Data and Results," Trans. S.N.A.M.E., 1940, page 125.
28. Dahlmann, W. and Remmers, K., "Beitrag Zur Festigkeitsmessung am Fahrenden Schiff," Schiffbau, Schiffahrt und Hafenbau, 1 January, 1940 (U.S. Experimental Model Basin Translation No. 97).
29. ————, "Structural Investigation of the Tanker *S.S. Shiloh*," U.S. Maritime Commission Report (unpublished).
30. ————, "Structural Investigation of Great Lakes Ore Carriers," U.S. Maritime Commission Report (unpublished).
31. ————, "Structural Tests on the *S.S. Philip Schuyler*," U.S. Maritime Commission Report (unpublished).
32. Vasta, J., "Structural Tests on the Liberty Ship *S.S. Philip Schuyler*," Trans. S.N.A.M.E., 1947, page 391.
33. ————, "Structural Tests on the *S.S. Ventura Hills*," U.S. Maritime Commission Report (unpublished).
34. Vasta, J., Discussion, Trans, I.N.A., 1946, page 136.
35. Vasta, J., Discussion, Trans. S.N.A.M.E., 1949, page 470.
36. Bull, F. B., Shepheard, R. B. and Turnbull, J., "Structural Investigations in Still Water on the Welded Tanker *Neverita*," Trans. I.N.A., 1946, pages 59 and 78.
37. Admiralty Ship Welding Committee Report No. R1, "Report on Hogging and Sagging Tests on All-Welded Tanker M. V. *Neverita*," 1946.
38. Shepheard, R. B. and Bull, F. B., "Structural Investigations in Still Water on the Tanker *Newcombia*," Trans. N.E.C.I.E.S., 1946–47, page 237.
39. Admiralty Ship Welding Committee Report No. R2, "Report on Hogging and Sagging Tests on Riveted Tanker *M.V. Newcombia*," 1948.
40. Boyd, G. M., Bull, F. B., and Pascoe, K. J., "Preliminary Experimental Voyage of the Tanker *Niso* Under Winter North Atlantic Conditions," Trans. I.E.S.S., 1947–48, page 178.
41. ————, "Structural Tests on the *S.S. Fort Mifflin*," U.S. Maritime Commission Report (unpublished).
42. Bull, F. B., Baker, J. F., Johnson, A. J., and Ridler, A. V., "Measurement and Recording of the Forces Acting on a Ship at Sea," Trans. I.N.A., 1949, pages 29 and 55.
43. Admiralty Ship Welding Committee Report R6, "Structural Tests in Still Water *S.S. Ocean Vulcan*," 1952.
44. Admiralty Ship Welding Committee Report R7, "Structural Tests in Still Water on *S.S. Clan Alpine*," 1952.
45. Admiralty Ship Welding Committee Report R8, "*S.S. Ocean Vulcan* Sea Trials," 1952.
46. Johnson, A. J., "Vibration Tests of All-Welded and All-Riveted 10,000-ton Dry Cargo Ship," N.E.C.I.E.S., 1950–51, page 205.
47. Vasta, J., "Structural Tests on Passenger Ship *S.S. President Wilson* — Interaction between Superstructure and Main Hull Girder," Trans. S.N.A.M.E., 1949, page 253.
48. Lang, D. W. and Warren, W. G., "Structural Strength Investigations on Destroyer *Albuera*," Trans. I.N.A., 1952.
49. Turnbull, J., "Longitudinal Strength," Trans. I.N.A., 1952.
50. Wright, E. A. and Vasta, J., "Structural Behavior in Ships," Journal of the American Society of Naval Engineers, November, 1952, page 693.
51. Howe, E. D., Boodberg, A. and O'Brien, M. P., "History of Residual Stresses in Welded Ships, Part II—Hogging and Sagging Tests of Oil Tankers," Office of Scientific Research and Development Report No. 5262, Serial No. M-494.
52. Howe, E. D., Boodberg, A., York, B. and O'Brien, M. P., "History of Residual Stresses in Welded Ships, Part III —Tests of Two Liberty Ships at Sea," Office of Scientific Research and Development Report No. 6359, Serial No. M-586.
53. Howe, E. D., Boodberg, A. and O'Brien, M. P., "History of Residual Stresses in Welded Ships, Part IV—Hogging and Sagging Test of an Oil Tanker and Stress Measurements on Type C-4 Troopships," Office of Scientific Research and Development Report No. 6587, Serial M-623.
54. King, J. F., "Ship Experiments and Theories," Proc. of the World Engineering Congress, Tokyo, 1929, Vol. 29–30.
55. Jasper, N. H., "Study of the Strain and Motions of the USCGC *Casco* at Sea," D. W. Taylor Model Basin Report No. 781.
56. Laws, B. C., "Notes on the Behavior of Two Passenger Vessels During a Voyage to and from Australia," Trans. I.N.A., 1930, page 99.
57. Vedeler, G., "Notes on the Structural Design of Tankers," European Shipbuilding, Vol. I, No. 1, 1952, page 7.
58. Final Report of the Board of Investigation to Inquire Into the Design and Methods of Construction of Welded Steel Merchant Vessels, Government Printing Office, Washington, D.C., 15 July, 1946.
59. Brown, D. P., "Observations on Experience with Welded Ships," The Welding Journal, September, 1952.
60. Murray, J. M., "Corrugation of Bottom Shell Plating," Trans. I.N.A., 1954.
61. Schnadel, G., "Elastizitätstheorie und Versuch," Jahrbuch der Schiffbautechnischen Gesellschaft, 1931.

TABULATION OF FULL SCALE SHIP TEST DATA

Date	Ship	Ship Type	Construction	Loading	DATA			Notes	Ref.
					Type	Method	Location		
1903	WOLF	200' Destroyer. Single deck	Transverse framing, 20" spacing. All riveted.	Known hogging and sagging B.M. imposed on vessel by changing water level.	Fore and aft strains	Stromeyer (mechanical) strain gage, 20" G.L.	30' aft of amidships, also about amidships only few gages below N.A. In general, stresses read on both sides of plating.	Reduced effective E determined for I incl. all longitudinally continuous material less rivet holes on tension side of N.A. Stress distribution generally in accord with beam theory. Max. deflection about 3". Vessel returned to original form upon unloading. Subsequently Hoffman reasoned thin plating in compression buckled reducing effective Ship I. E used would then be that of material.	1. 6. 9.
					Ship Deflections	Battens on ship read from dock	11 positions fore and aft		
				Vessel in seaway Moderately rough weather	Fore and aft strains	Stromeyer strain gage.	30' aft of amidships. 3 locations; keel and deck, port and starboard	Calibration of ship in dock via strains the means of inferring B.M. in a seaway. Sagging moments greater than hogging. Keel stresses greater than deck. Very small stresses set up by rolling and those during pitching and rolling less than for pitching alone. Actual stresses in rough weather much less than those calculated for standard L/20 wave e.g. keel, 5.38 vs. 7.14; deck, port, 2.88 vs. 5.30; deck, starboard, 2.14 vs. 5.30 tons/in. Period of encounter about 6 - 8 seconds at fastest speed viz. 13.2 knots. Stresses highest at highest speeds.	
1913	ANCON			Vessel in seaway. Full load outward bound; 1/3 load homeward Weather fair		Scissors gage, 6" G. L.	Deck at quarter points; port side and at break in bulwark rail	Strains greater with increasing pitch. No estimate of bending moment or weight distribution date given.	2.
				Loading cargo	Fore and aft strains 20" G. L.	Telescopic gages	Deck and rail at after quarter point, port and starboard.	Strains due chiefly to temperature variations; little if any due to loading cargo.	
1913	NEPTUNE	Collier	Transverse framing	During launching, fitting out and docking	Ship deflections	Transit sights	Several stations fore and aft	No bending moment or weight distribution data given.	3.
	ORION	Collier	Longitudinal framing						
	JASON	Collier	Longitudinal framing						
1915	ULYSSES	Collier		On the ways, during launching, fitting out and docking	Ship deflections	Transit sights	Several stations fore and aft	No bending moment or weight distribution data given. Considerable question as to the effects of temperature variations on the ship deflection.	4.
	ACHILLES	Collier							
	ATLANTIC	Freighter							
1918	FAITH	Cargo Ship	Longitudinal framing Reinforced concrete	Vessel in seaway. one voyage. Moderately rough weather	Fore and aft strains	Recording extensometers	8 points	Maximum range of stress 3.1 tons/in^2.	5.
1919	WESTBORO	410' - 6" Cargo Ship Three decks	Transverse framing	Vessel in seaway. one voyage.	Fore and aft strains	Recording extensometers	Up to 22 points simultaneously in a transverse section amidships.	Maximum range of stress about 3.6 tons/in^2. 2000#/in2. stress increase due to pounding indicated.	
1926	PROMETHEUS	430' Cargo Vessel. Bridge superstructure 30% of vessel's lngth.	Transverse framing except longitudinal at bridge deck.	Known hogging and sagging B.M. imposed on vessel in still water.	Fore and aft strains	Extensometers, 120" G.L.	In 10 pairs, port and starboard, over majority of ship's length; 3 pairs at bridge deck, 6 at upper deck and 1 on tank top	Vessel built entirely of higher strength steel. Some comparisons made with data from similar vessel built of ordinary mild steel. Stresses from measured strains compared to calculated stresses involving known B. M. and various I values. Maximum values of stress (bridge sheerstrake, amidships) 4.8 tons/in.^{2} tension and 1.89 tons/in. ^{2} compression. Conclusion that simple beam theory may be confidently used for sizing scantlings particularly those under tension.	54.
					Ship deflections	Line of sights			
1926		235' Collier 390' Freighter 400' Tanker 440' Tanker	Transverse framing. " " Longitudinal framing.	Loading and discharging cargo.	Fore and aft strains	Mechanical strain gages. 24"-36" G.L.	Region of uppermost deck (one exception)	Bending moments calculated. Stress calculated from observed strain and modulus of 13,000 tons/in^2. Virtual section modulus calculated from strains and bending moments above. Strains observed at no more than four positions. Bending moments relatively small. No temperature compensation.	7.
	LONDON MARINER KENMORE	450' Express Freighter 363' "		Vessel in seaway. One voyage. Weather fine to moderate.	Wind velocity and period of wave encounter.	Anemometer and stop watch.		No weight distribution nor bending moment data.	
					Pitch and roll angles and periods.	Bubble level.			
					Ship speed	Log and stop watch.			
					R. P. M.	Stop watch			
					Fore and aft strains. (Maximum values)	Mechanical strain gege. 24"-36" G.L.	Uppermost deck and sheer stroke.		
	SAN TIRSO SAN FRATERNO	420' Tanker 420' Tanker		Vessel in seaway. Fairly rough weather. Waves about 35' high.	Same as for London, Mariner, and Kenmore except no speeds or R.P.M.	Same as for London, Mariner and Kenmore.	Fore and aft strains taken in deck, sheer strake, bilge, bottom and keel; all near amidships.	No more than 4 strain gages used simultaneously. Maximum stress range 10.5 tons/in^2 vs. 12.7 tons/in^2 for standard wave, i.e., about 6.7 tons sagging, 6.0 tons hogging.	
				Undocking or discharging cargo.	Ship deflections.	Telescope sight.	Several positions fore and aft on deck.	Account taken of shear deflection in calculation.	

Date	Ship	Ship Type	Construction	Loading	Data			Notes	Ref.
					Type	Method	Location		
1927		Car float	Transverse framing, 24" spacing, plus 6' full depth longitudinal girders.	Thermal	Hull deflections.	Transit sights.	Deck, port and starboard	Data taken throughout one day. Temperature compensation formula for deflection proposed.	8.
				Hogging moment imposed in still water.	Fore and aft strains.	2 mechanical strain gages, 20" G.L.	40 stations, mostly amidships. Some fore and aft in stringer plate.	For ship I with all material considered fully effective except rivet hole area in tension, calculated stresses 10% greater than determined via strain measurements. Strain gages not located to insure determination of heart of plate stresses. Fairly good agreement between calculated and observed deflections when corrected for temperature.	
					Hull deflections.	Transit sights.	Deck, port and starboard		
1928		550' Cargo Passenger Vessel with extensive superstructure. 600' Cargo Passenger Vessel with extensive superstructure.	Transverse framing	Vessels in seaway. One voyage, England to Australia and return. Seas up to moderately heavy.	Fore and aft racking of superstructure (first vessel only).	Taut wire	Forward end of superstructure, port and starboard.	Largest waves encountered 300' x 10'-12'. Maximum average wind velocity 34 m.p.h. Concluded that ratio of maximum measured stress to standard calculated stress about 1.5 and with mean values of measured stress, 1.25. For first vessel in a fresh gale, pitching angle $\pm 2\frac{1}{2}^{o}$, maximum angular acceleration 0.0209 ft./sec.^{2}, complete period 8.8 seconds; rolling angle $\pm 3\frac{1}{2}^{o}$, maximum angular acceleration 0.0042 ft./sec.^{2}, complete period 20.4 seconds. Transverse racking displacements not measured but were greater than fore and aft although transverse angular acceleration 1/4 that fore and aft. Deck strains not read simultaneously.	56.
					Fore and aft strains	Recording mechanical strain gage	Uppermost continuous deck, amidships and just clear of superstructure forward (also first deck above, amidships, of second vessel).		
					Roll and pitch angles and periods	Pendulum and "pitch indicator" respectively			
					Wind velocity, wave length, height and direction.	Visual observations for waves			
					Ship speed	Log			
1929		425 Shelter deck cargo vessel.	Transverse framing.	Vessel in seaway. One voyage. Outward bound in ballast; homeward bound, loaded. Weather severe.	Pitching and rolling.	Pendulums		Maximum angles; pitch, 9°, roll, 19°.	10.
					Uniaxial strains	Recording mechanical strain gage.	Various locations and directions.	Tests performed primarily to evaluate local effects rather than general behavior. Determination of racking showed negligible amounts. Transverse frame deflections measured. Some random service stress and estimated wave proportion data given. Transverse stresses small but stress concentrations in way of discontinuities and importance of transient impacts considered to be appreciable.	
1929	GOTTINGEN	Cargo Ship	Transverse Framing	Vessel in seaway.	Fore and aft strains.		At break in bulwark, forward of amidships.		11.
					Wave profile.				
					Pitch and roll.				
1930	ODIN	Cargo Vessel Two Decks	Transverse framing. All riveted.	Vessel in seaway. Sea calm	Fore and aft strains.	Dial gage extensometers.	Across upper and second decks, in side shell between decks and just below neutral axis.		12.
					Ship deflections.	Telescope sight.	Forward side of bridge		
1930	CUYAMA	455' Tanker	Transverse framing. 27" spacing keelsons and side stringers. All riveted.	Known static bending moment in still water.	Ship deflections.	Telescope sight and cantilever extending 70' aft of bridge.	On deck.	Known B. M. and inferred stress in deck gives section modulus 4% less than standard calculation. From calculated position of neutral axis and mensured deflection, E = 24,000,000 lbs /in^2. Average B. M. over selected span assumed constant in relating B. M. to deflection for EI. No correction for shear deflection. Maximum B. M. – 120,000 to 125,000 tons ft. or about 1/2 range of design B. M. Section modulus values increase slightly with B. M. No temperature corrections since readings taken at approximately constant temperature.	13. 16.
					Fore and aft strains.	3 Extensometers 300" G. L.	Upper surface of deck only.		
				Vessel in seaway for 50 days. weather mostly fine.	Fore and aft strains.	3 Extensometers associated with rheostat type automatic recorder.	Upper surface of deck only.	B. M. for sea conditions inferred by comparing strains at sea with those under known. B. M. in still water. Approximate maximum seaway B. M. encountered; 56,000 tons ft. sag and 73,000 tons ft. hog. Normal deep load still water. B. M. 120,000 tons ft. sag. Design B. M. (total), 234,740 tons ft. Seaway hogging moments greater than sagging. Buckling occurred in deck plating. For most part, only maximum values of strain measured. Instrument activated thus for 9-1/2 minutes then arranged to give continuous readings for 1/2 minute and released.	14. 16.

Date	Ship	Ship Type	Construction	Loading	Data: Type	Data: Method	Data: Location	Notes	Ref.
1930	PRESTON	310' Destroyer single deck	Transverse framing, 21" spacing All riveted.	Known sagging B.M. imposed on vessel by changing water level in dock and ballasting.	Multi-directional strains.	Portable mechanical gages. 10" G. L.	Girthwise around vessel at 3 stations; one at each quarter point and one amidships.	Vessels tested to ultimate load. PRESTON deck and longitudinals buckled at B. M. of 44,000 tons feet. Corresponding inferred stringer plate stress, 13.7 tons/in². (Design B.M., 12,300 tons ft.) BRUCE bottom plating buckled at B.M. of 36,000 tons ft. Corresponding inferred stress, 10.35 tons/in². (Design B.M., 18,600 tons ft.) Close agreement between fiber stresses as calculated and as inferred from strain measurements. Beam theory stress distribution valid. Therefore I calculation with no rivet hole deductions, all continuous structure effective and full allowance for lightening holes justified. At ultimate loads, 3% apparent reduction in I probably due to plating buckling. Heart of plate stresses found by measuring strains at plate surface and on buttons of known thickness Not such good agreement between inferred and calculated shear stresses. Observed and calculated total deflections based on E of material and I as above in good agreement. Shear deflection 8-10% of total deflection. All readings and tests made at night so limiting temperature difference to 8°.	15. 27
					A few fore and aft strains.	Dial gage with mechanical magnification. 300" G. L.			
					Ship deflections	Theodolite	Keel and deck edge, port and starboard.		
					Transverse change of shape.	Dial gages.	Amidships.		
1931	BRUCE	Identical to PRESTON	Identical to PRESTON	Same as PRESTON but hogging.	Same as PRESTON.	Same as PRESTON.	Same as PRESTON.		
1934	SAN FRANCISCO	430' Cargo-passenger vessel. Three decks superstructure 25% of vessel's length.	Transverse framing. All riveted.	Vessel in seaway. Hamburg-Panama Canal - Vancouver and return. Very rough weather.	Shape, length and height of waves.	Electric contacts on on shell lighting lamps simultaneously photographed.	Stations 66' apart fore and aft; 12"-16" apart vertically.	Boyancy distribution determined from bottom pressures and ship weight distribution altered to suit, the difference being the acceleration component due to ship oscillation. These accelerations checked by accelerometer. Buoyancy and virtual weight curves yield bending moments and stresses for comparison with those measured. (Strains read on both surfaces of plating.) Similarly, deflections deduced from bending moments compared with those measured. Transverse strains taken into account by increasing E 2.5% for influence of transverse stiffening. Hogging bending moment reduced but sagging bending moment increased by dynamic forces. Therefore, ship hove to worst reasonable condition for hogging but steaming ahead worse for sagging. Maximum stresses when ship among waves of ship's length. Then maximum values in deck, 9250 lbs/in² tension and 13100 lbs/in² compression. (Compressive stress includes 2700 lbs/in² in transient pounding loading.) Good agreement between deduced hogging bending moments and strains. Not so good for sagging. Satisfactory agreement between observed deflections and those calculated including shear deflection and dynamic effects. Maximum pitching angles + 12° to - 10°. Maximum angle of roll 20°. Maximum heaving acceleration 8.2 ft/sec². One wave encountered 610' x 54' in which ship center of gravity oscillated 39.4'. Pounding shocks noted.	17. 21. 26. 20. 19. 18.
						Stereo-photographs			
					Pressure on ship's bottom.	Flexible diaphragms operating scratch recorders.	8 stations.		
					Accelerations, rolling and pitching angles.	Recording, pendulum type accelerometers and gyroscopes.	About 5 positions throughout length of ship; port and starboard (accelerations)		
					Ship deflections.	Continuous photographic record of 8 light sources.	Light sources spaced over major portion of ship's length, uppermost deck, port.		
					Strains fore and aft and at 45°.		A few positions on uppermost deck, mostly on stringer plate, port, and at a point somewhat forward of amidships and below the neutral axis.		
					Deflection of deck and bottom plating panels.				22.
1935-36	BEAVERBRAE	495' Cargo Vessel superstructure 25% of vessel's length. Two complete decks.	Transverse framing.	Vessel in seaway. Two voyages. London-Halifax and return. Rough weather.	Uniaxial strains (Fore and aft in deck)	Portable strain meter 3" G. L.	Superstructure house ends.	Zero strains for vessel in drydock. Readings taken during loading and at sea whence strains represented aggregate imposed values. Length of longest waves encountered about half ship's length. Decreasing period of encounter increased transient peaks of stress. Therefore, with longer waves, (up to ship's length), mean range of stress higher but ratio of maximum to mean stress ranges probably lower because encounter period more nearly synchronous with vessel's pitching period thus reducing pounding and shipping of water. Reducing speed analagous. Transient stress peaks up to about 1-3/4 tons/in² in excess of mean peaks. Maximum range of stress on deck amidships, clear of discontinuities, 5 tons/in². Maximum angle of roll, 30°. Maximum angle of pitch, 7°.	23.
						4 dial gage extensometers. 72" G. L.	On upper deck in way of house front forward of amidships and abreast of house, amidships.		
1935	DEWEY	334' Destroyer Forecastle. 33% ship's length	Longitudinal framing	Vessel in seaway	Strains (Fore and aft?)	At 50 stations by recording scratch gages of latch-key type. Maximum and minimum values over one or two pitching cycles taken simultaneously at 18 stations with Huggenberger gages.	Two transverse sections; amidships and 38% vessel's length from bow.	Scratch gage data inconsistent. Only small bending loads encountered. Maximum stress range about 4.5 tons/in². Rather definite evidence that neutral axis lies above its calculated position. Little information given.	24.
					Ship deflections	Photographing row of lights	Lights extending over 55% vessel's length		
1936	FLUSSER	334' Destroyer Forecastle 33% ship's length		Vessel in seaway	Strains, mainly fore and aft but at two points in side plating strains read at 45° and 135° to neutral axis.	Recording scratch gages of latch-key type and one rosette of mechanical gages, photographically recorded.		Strain data not extensive and of very small magnitudes although including some for shear. Not feasible to do more than follow range of stress variation. Little information given.	
				Known static bending moments in still water	Strains			Bending loads small. Very little information given.	
					Ship deflections				

Date	Ship	Ship Type	Construction	Loading	Data			Notes	Ref.
					Type	Method	Location		
1937	SAN CONRADO	460' tanker	Combination framing; longitudinal, deck and bottom; transverse sides.	Vessel in seaway. One voyage. Outward bound in ballast; homeward, full. Weather; fairly severe to moderate.	Fore and aft strains	2 dial gage extensometers 30" G.L. and one portable strain gage 3" G.L.	Upper surface of deck plating. During rough weather; within short bridge house on ship center line only.	Maximums, minimums and mean values of strain read, also the time taken for a number of such cycles. Maximum range of stress measured (In bridge house, forward of amidships) 4.3 tons/in^2. Estimated wave dimensions given and related to stresses. Mean range of stress appears to reach a maximum at wave lengths equal to ship's length but isolated maxima probably increase with increase of wave proportions. Athwartship strains found to be negligible. Maximum angle of roll, 18° Maximum angle of pitch, 9°	25.
1938	BAGLEY	334' destroyer, forecastle 33% ship's length		Vessel in seaway	Strains	Recording scratch gages of latch-key type.		Time capacity of gages increased over those used previously. Bending moments of significant value obtained. Very little information given.	24.
1939	PHOENIX	600' light cruiser		Vessel in seaway. Weather calm	Strains	Recording scratch gages of latch-key type. Stress counter		Stress counter designed to keep cumulative count of number of times stress exceeded predetermined value. Very little information given.	
1939	DUISBURG	465' cargo vessel 2 complete decks. Superstructure 25% of vessel's length	Transverse framing	Loading cargo	Strains (mostly tri-axial) 7.9" G.L.	Photographic recording of Zeiss "ortho-test" instrument dials	7 points throughout ship depth but arranged in two transverse planes aft of amidships 35' apart.	Ship loading proceeds uniformly throughout length. Resulting strains, ship deflections and plate panel deflections very small. Data on thermal straining given.	28.
					Ship deflections	Theodolite	Deflection of point amidships from line of sight 194' long.		
					Plate panel buckling	Dial gages	Various points on shell		
				Vessel in seaway. Weather calm	Ditto for condition loading cargo.	Ditto for condition loading cargo.	Ditto for condition loading cargo.		
1943	SHILOH	503' tanker (T2 type) Bridge superstructure 7% of vessel's length	Longitudinal framing, fluted bulkheads. All welded	Known hogging and sagging B.M. by filling various tanks in still water	Strains, mostly bi-axial at 325 points	Mechanical strain gages 2" and 10" G.L. Electric resistance gages 1" G.L.	Mainly in way of midship section. Also on stringer plate aft, bridge deck fashion plate aft, bridge deck and longitudinal-transverse bulkhead intersection.	Maximum bending moments imposed about equal to vessel fully loaded on standard wave, viz. 279,000 tons ft. hogging, and 209,000 tons ft., sagging. All strain readings taken at night. Hence, range of structure and air temperatures not greater than 6°. Considerable data unreliable but stress distribution essentially as for simple beam theory. Measured stresses less than calculated by 17% in hogging and 9% in sagging. May be due to discrepancy in computed moment of inertia, computed B.M., accuracy of instruments and methods or reading strains on one side of plate only. No conclusion relative to effectiveness of longitudinal bulkhead in shear. No excessive stresses in deck at transverse bulkheads or in bridge fashion plate aft. Bridge deck stresses less than in upper deck. Notable stress concentrations at longitudinal-transverse bulkhead intersections. In hogging, measured deflection 10% less than calculated. In sagging, fairly good agreement. Calculated deflections are for bending only; excluding shear.	29.
					Ship deflections	Transit sight	Transit on poop, targets amidships and forward		
1943	PURNELL CADILLAC	Identical 595' Great Lakes ore carriers	Combination framing. All welded except riveted side shell seams.	All loaded similarly under one hogging and one sagging B.M. in still water	Strains in rosettes at least in way of local stress concentrations	Dial gages 10' to 48' G.L. Mechanical gages 2" and 10" G.L. Huggenberger gages 1" G.L.	In each midship section plane and various localized areas. Also near after quarter point in side shell of CADILLAC	All readings taken at night. No unusual departure from simple beam stress distribution noted. The combination riveted and welded structure works integrally and in a homogeneous manner. Negligible longitudinal stresses in deck plating between hatches. Local areas of strain measurement included main deck access door opening, cargo hatch opening, hatch coaming and gunwale.	30.
	CHAMPLAIN HUTCHINSON	Identical 605' Great Lakes ore carriers							
1944	ELK HILLS ANTELOPE HILLS	503' Tanker (T2 Type) Bridge superstructure 7% of vessel's length. All welded.	Longitudinal framing, fluted bulkheads	Known hogging and sagging B. M. imposed on vessels in still water	Strains in rosettes	Electric resistance strain gages 13/16" G. L.	Top and bottom surfaces of deck plating at each of 18 points in way of center and wing tanks amidships.	Primary purpose to evaluate effect of still water hogging and sagging on locked in stresses due to welded construction. Sequence of B. M. values at test section in neighborhood of from 145,000 tons ft. hogging to 280,000 hogging to 175,000 sagging to 155,000 hogging. Corresponding maximum calculated tensile stress due to hogging 13,500 lbs./in.^{2}. (Reference FULLERTON HILLS)	51.
1944	GEORGE B. McFARLAND SAMUEL GOMPERS	416' Cargo Ships (Liberty) Two decks, superstructure 20% vessel's length. All welded.	Transverse framing, 30" spacing. Predominantly welded. Gunwale angles riveted.	Vessels in seaway. Each on maiden voyages. North Pacific 4 & 6 months.	Strains mostly rosettes	Electric resistance strain gages	Top and bottom surfaces of upper deck plating at each of 18 points plus 5 on each of two hatch corners. All nearly amidships.	Primary purpose to evaluate effect of service conditions on locked in stresses due to welded construction but B. M. encountered only moderate and results gave no positive evidence.	52

Date	Ship	Ship Type	Construction	Loading	Data: Type	Data: Method	Data: Location	Notes	Ref.
1944	PHILIP SCHUYLER	416' cargo ship (Liberty) Two decks superstructure 20% vessel's length	Transverse framing 30" spacing. All welded except shell-frame connection riveted	Known hogging, sagging and torsional moments applied in still water	Strains in rosettes	About 200 electric resistance strain gages 13/16" G.L. and about 200 mechanical gage stations. 2" and 10" G.L.	In way of #3 hatch, forward of amidships at decks, sides, inner bottom and bottom shell. Also extensive readings in bottom shell amidships and in way of #3 hatch corners.	Strains read only at night. Only one sagging condition of loading. Data taken and discussed for hogging conditions only, maximum of which was 134,000 tons ft. or about 80% standard bending moment. Second deck and inner bottom attained 50% theoretical beam theory stresses resulting in 5% reduction in predicted Ship I and correspondingly small increase in predicted deck and bottom stresses. High degree of transverse strain restraint in main deck but not in side shell i.e. biaxial tension in deck but uniaxial in side. Initially bulged plating in bottom brought about peaks and hollows of heart of plate stress under compressive loading. Most severely bulged panel took on permanent set. Thereaftes stress distribution in bottom plating became symmetrical about the keel but average stress loading accepted by it somewhat reduced apparently to be borne by other members such as vertical keel and side girders. Average stresses in fair agreement with beam theory distribution reaction to tensile loading. Torsion tests showed nothing unusual. Torsional moment and shear stresses low.	31. 32.
					Plate panel deflections	Sagitta gage 10" G.L.	At all points of strain measurement except hatch corners.	Plate panel deflections measured and associated with strains read on one plate surface only in order to deduce heart of plate stresses.	
					Ship deflections	Transit sights	Surveyor's level rod at 16 stations port and starboard on deck.	Ship deflections read during the day. Calculated shear plus bending deflections agree well with those observed when corrected for temperature. Shear deflection about 15% of total.	
1944	NEVERITA	460' tanker. Bridge superstructure 10% of vessel's length	Combination framing; longitudinal framing in deck and bottom, transverse framing in sides and bulkheads. All welded except shell-frame connection riveted	Various known hogging and sagging B.M. imposed on vessel in still water	Strains, fore and aft and in rosettes	Mechanical gages 5" G.L. Mechanical extensometers 100"-120" G.L. Electric resistance gages 13/16" G.L. Acoustic gages 4 3/4" G.L.	Transverse section amidships, between frames and webs at mid length of tank.	Range of bending moments applied; 158,000 tons ft. hogging to 86,000 tons ft. sagging. Plate panel deflections and surface strains used to determine heart of plate stresses. Electric resistance strain gage results not considered reliable. Stress variation fairly close to beam theory prediction. Transverse stresses 20% of longitudinal stresses noted. High local bending deflections and stresses sufficient for plastic yielding in transversely oriented bottom plating panels. Bending stresses much higher than heart of plate stresses in such panels. With all continuous material included in I and modulus of elasticity taken as that for the steel, calculated ship deflection including bending and shear about 10% greater than measured. Heart of plate stress of 1 ton/in² in deck appears to have been induced by 30° temperature difference between deck and bottom. Temperature range small during taking of data.	36. 37.
					Plate panel deflections	Mechanical arc rise gage, 6" G.L. "Mushroom" slope difference lever system 3" G.L.	Same as for strains	NEVERITA - NEWCOMBIA Comparison Stress distribution and longitudinal deflections in the two forms of construction show no major differences. Local bending stresses in the particular panels examined were in general less in the riveted ship owing to fairer plating and the stiffening influence of riveted overlaps. Stress concentrations around large structural discontinuities approximately the same for the two forms of construction.	
					Ship deflections	Theodolite, water-level tubes and drafts.	About 6 stations fore and aft (except drafts)		
					Thermal effects	Thermometers and thermocouples			
1945	NEWCOMBIA	460' tanker similar to NEVERITA	Similar to NEVERITA but all riveted except deck plating butts, sheer to stringer plate connection, longitudinal bulkheads to bottom plating, longitudinal stringers to side shell and longitudinal bulkheads also various brackets.	Similar to NEVERITA	Same as NEVERITA except no examination for thermal effects			Range of bending moments imposed about 80% range calculated for vessel on standard L/20 wave. Results from electric resistance gages more satisfactory than in NEVERITA. Probably fairly even temperatures throughout ship during observations. Stress distribution fairly close to beam theory. Transverse stresses averaged about 1/6 longitudinal stresses, i.e. about 50% product of Poisson's ratio and longitudinal stress. Little vertical shear carried by other than side shell and longitudinal bulkheads. Average shell plating unfairness about 6% of plate thickness, i.e. negligible. Probably because of this greater fairness than in NEVERITA, local bending stresses less. Plating unfairness has little effect on local bending stresses from lateral water pressure loading. Local bending stresses sometimes greater than heart of plate stresses. Where axial stresses are imposed on plating having initial deflection due to unfairness or lateral pressure, total stresses do not conform to Principle of Superposition. For Ship I and E, as for NEVERITA, total calculated ship deflection about 6% greater than measured. Shear deflection averaged 7% bending deflection.	38. 39.
1945	VENTURA HILLS	500' tanker (T2 Type) Superstructure 7% of vessel's length.	Longitudinal framing, fluted bulkheads; all welded.	Known hogging and sagging B.M. imposed on vessel in still water.	Strains in rosettes.	Mechanical gages 10" G.L. Electric resistance gages 13/16" G.L.	Transverse section about 76' aft of amidships. Also in way of longitudinal-transverse bulkhead intersections.	Range of applied bending moments; 221,000 tons ft. sag to 284,000 tons ft. hog, i.e., about 100% bending moment on standard wave. Corresponding values at test section; 48,000 tons ft. sag, 199,000 tons ft. hog, 2400 tons and 2340 tons shear force. Direct and shear stress distribution throughout in good agreement with beam theory. Longitudinally fluted fore and aft bulkheads carry full share of bending moment and shear force. Web intersection of longitudinal, and transverse bulkheads carry full share of shear load but not bending load.	33. 34. 35.
					Plate panel deflections	Sagitta gage 10" G.L.	Transverse section 76' aft of amidships.		
					Ship deflections	Transit sights	On deck over a 330' length of ship.		
1945	FULLERTON HILLS	503' tanker (T2 Type) Bridge superstructure 7% of vessel's length. All welded.	Longitudinal framing, fluted bulkheads	Known hogging and sagging B.M. imposed on vessel in still water	Strains in rosettes.	Electric resistance strain gages.	Top and bottom surfaces of deck plating at each of 18 points in way of center and wing tanks amidships.	Primary purpose to evaluate effect of still water hogging and sagging on locked in stresses as with ELK HILLS and ANTELOPE HILLS but unlike them conclusion reached that no relief took place despite larger range of B.M. Sequence of B.M. at test section; from 128,000 tons ft. hogging to 6,800 to 270,000 to 187,000 sagging to 130,000 hogging.	53.
					Ship deflections	Transit sights	At 9 stations between forecastle and poop, port.		
	GENERAL OMAR BUNDY	496' Troopship (C4 Type) Machinery aft	Transverse framing. Predominantly welded.	Vessel briefly in seaway undergoing trials.	Fore and aft strains.	Electric resistance strain gages.	Top and bottom surfaces of main deck at each of 4 points plus few others in stringer and shear strake.	No B. M. data. (Relaxation strain data only given for three other vessels). Apparently little or no reduction of stress in welds from short term service experience of vessels although bending stresses encountered thought to be sufficient (probably because of previous stress relief from handling subassemblies during fabrication).	

Date	Ship	Ship Type	Construction	Loading	Data			Notes	Ref.
					Type	Method	Location		
1944-45	NISO	460' tanker. Bridge superstructure 10% of vessel's length	Similar to NEWCOMBIA	Vessel in seaway. One voyage outward bound in ballast. Weather moderate to fairly severe	Direct strains	Extensometer with dial gage and remote reading extensometers with variable induction choke as well as electric resistance gages	On deck amidships and various other locations	Voyage of exploratory nature to determine suitability of various instruments and ranges of values to be expected. Relative merits of each briefly discussed. Maximum angle of roll ± 12°, pitch ± 6°.	40.
					Ship deflections	Ciné camera and target boards	Camera on poop, target boards on forecastle and after end of bridge		
						21' steel trusses for deflection references and hinged 80' trusses. Both types remote reading	On deck forward		
					Water pressure on hull	Diaphragm type pressure gage with remote reading variable inductance choke.	Forward of bridge		
					Wave profile	Series of electrical contacts on ship's side closed by presence of sea water.	One vertical row, amidships		
					Wind forces	Deflecting wind board with remote reading variable inductance choke.			
					Accelerations	Tridirectional accelerometer, using unbonded electric resistance strain gages.			
					Roll and pitch angles and periods.	Gyroscope and 2 stereoscopic cameras	Cameras port and starboard on bridge.		
1945	FORT MIFFLIN	503' tanker (T2 type) Bridge superstructure 7% of vessel's length	Logitudinal framing, fluted bulkheads (Identical to VENTURA HILLS)	Known hogging and sagging B.M. imposed on vessel in still water	Strains in rosettes	Mechanical gages 10" G.L. Electric resistance gages.	Transverse section about 60' aft of amidships and in way of logitudinal - transverse bulkhead intersection. Generally on one surface only.	Range of applied moments, amidships; 282,000 hogging, 215,000 sagging vs 168,000 hogging and 230,000 sagging for ship fully loaded and on standard L/20 wave. 282,000 tons ft. amidships corresponds to 228,000 ton ft. at test section plus 1,760 tons shearing force. Sagitta gage readings with strain readings permit solution for heart of plate stresses. All observations made at night. Remarkable agreement with results from VENTURA HILLS. Effectiveness of two types of bracket at longitudinal-transverse bulkhead intersection evaluated. One 12'-2" x 30" panel of 3/4" plating in bottom examined. Built in deflection 14% thickness. Additional deflection linear with water head reaching 3% additional for 27' head. Any increment due to edge compression loading too small to be measured. Agreement between measured and calculated hull deflections very good. Shear deflection and small temperature correction included. Temperature correction .058" deflection / ° F of air temperature for 414' length of ship	41.
					Plate panel deflections	Sagitta (arc rise) gage 10" G.L.	Transverse section 60' aft of amidships		
						Dial gages	Bottom plating panel		
					Ship deflections	Transit sights	On deck, port and starboard at 5 points on a 414' length of ship		
1946-47	OCEAN VULCAN	416' Cargo vessel. Two decks	Transverse framing. All welded except shell to frame connections	Vessel in seaway. 8 voyages Great Britain to U.S. and return. Westbound in ballast. Eastbound loaded.	Strains fore and aft and girthwise.	Electric resistance gages.	Sheer strake and inner bottom on station near amidships, both sides of plating	Data tabulated here recorded synchronously as well as ships speed, engine speed and shaft torque. Photographic recording speed for all data; 2 frames/sec. for 18 minutes before reloading. Other data recorded at random included stereoscopic photographs of sea conditions, observations with portable instruments of local stresses and accelerations as well as continuous record of stress reversals by statistical strain gage recorder. Water pressure distribution determined from pressure gages and wave profile indicators. Inertia forces determined from known distribution of mass and observed accelerations. Forces from water pressures and accelerations combined to give net forces making possible the computation of bending moments, shearing forces and torsion moments, etc. Most severe waves encountered estimated to be 600' x 35'. Corresponding ranges of values; vertical bending moment 190,000 tons ft., stress in sheerstrake 8 tons/in^2 (to be added to still water values). Horizontal and vertical bending frequently in phase but maximum values of one coincident with minimum values of the other. Torsion moments not over 1/2 ton/in^2 and not coincident with maximum vertical bending moments. Maximum fore and aft axial compression 1/2 ton/in^2. Probable slamming increment ± 1 1/2 tons /in^2 in sheerstrake. Heaving and pitching stresses negligible if unaccompanied by slamming.	42. 45. 49.
					Water pressure on hull	Photographic recording of meters connected to diaphragm type pressure gages	5-6 points around and below turn of bilge for 12 stations fore and aft.		

Date	Ship	Ship Type	Construction	Loading	Data			Notes	Ref.
					Type	Method	Location		
	OCEAN VULCAN (continued)				Wave profile	Electrical contacts on ships side closed by presence of sea water thus energizing telephone type indicators to be photographically recorded	30 points each side of ship at each of 12 girthwise stations throughout ship's length.		
					Wind forces	Wind vane generator output recorded	Deck house top and mast crosstrees		
					Accelerations	Recording tri axial electric strain gage type accelerometer.	4 Positions disposed fore and aft and athwartships		
					Angles of roll, pitch and yaw and periods	Recording gyroscopes			
1947				2.4 and some 3 node vertical and horizontal vibrations in still water	Critical frequencies, amplitudes and vibration profile.	Cambridge low-frequency and Geiger vibrographs and electric resistance strain gage accelerometers	On upper deck at 23 equidistant stations in ship's length	Records taken for seven differing displacements and loading distributions of ship including damping curves of free vibrations. Amplitudes measured for various magnitudes of exciting forces created by vibration generator at stern. For any particular mode of vibration, approximately linear relationship between maximum value of exciting force and resonant amplitude of vibration. In loaded ship conditions, resonant amplitudes per ton of exciting force do not differ appreciably from those in light ship conditions despite fairly large changes in frequency. Welded ship, OCEAN VULCAN, tends to have larger amplitudes than riveted ship, CLAN ALPINE, suggesting greater structural damping in riveted ship.	46.
				Known hogging and sagging B.M. applied in still water				Some apparent evidence of slightly greater ship deflections in welded OCEAN VULCAN than in riveted CLAN ALPINE. Unfairness of bottom plating between frames clear of longitudinal stiffening in CLAN ALPINE in general, about double that in CLAN ALPINE. Also more prominent stress deviations from beam theory in OCEAN VULCAN. In thin and abnormally unfair plating in transversely framed welded ship, surface stresses reached 3 times heart of plate stresses.	43. 49.
1947	CLAN ALPINE	416' Cargo vessel. Two decks (similar to OCEAN VULCAN	Similar to OCEAN VULCAN but all riveted	2 and some 3 node vertical and horizontal vibrations in still water	Same as OCEAN VULCAN	Same as OCEAN VULCAN	Same as OCEAN VULCAN	Records taken for four differing displacements and loading distributions of ship including damping curves of free vibrations. (For further details and comparisons of performance see OCEAN VULCAN notes.)	46.
				Known hogging and sagging B.M. applied in still water				(For comparison of performance see OCEAN VULCAN notes.)	44. 49.
1947	PRESIDENT WILSON	590' Passenger vessel. Multiple decks. Aluminum superstructure 35% vessel's length	Transverse framing Riveted shell and deck seams. Welded butts and shell-frame connections	Known hogging B.M. only applied in still water	Multi-axial strains	Electric resistance gages 13/16" G.L.	In superstructure, particularly at ends. Generally on both sides of plating	Maximum hogging moment applied, 202,000 tons ft. Sagitta gage readings with short gage length strains permit solution for heart of plate stresses in locations where strains not available for both plate surfaces. Primary objective to determine interaction between the superstructure and hull girder. Stress distribution linear with distance from neutral axis up to uppermost full-breadth deck but decreased thereafter as decks stepped inboard. Further marked reduction in stress in way of aluminum structure. Including longitudinally continuous material up through superstructure second deck in Ship 1 appears warranted from ship deflection analysis (despite low stresses in this uppermost deck). Shear deflection 20% of total. Conclusion that length of superstructure important in determining its strength contribution.	47.
					Fore and aft strains	Mechanical gage, 60" G.L.	Transverse section amidships, inner bottom to second deck of superstructure		
					Plate panel deflections	Sagitta (arc rise) gages 4" G.L.	A few points in superstructure		
					Ship deflections	Transit sights	Port and starboard on uppermost continuous deck. Deflections at 10 intermediate points along 476' line of sight.		

Date	Ship	Ship Type	Construction	Loading	Data			Notes	Ref.
					Type	Method	Location		
1949-50	ALBUERA	355' Destroyer. Single deck Forecastle, 43% vessel's length	Longitudinal framing. All riveted	Known hogging and sagging B.M. applied in still water	Strains			Constant draft maintained for all loadings also constant shearing force at test section. Maximum bending moments 39,000 tons ft. hogging, 30,000 tons ft. sagging. Corresponding maximum stress of 5½ tons/in² attained. Stress distribution at forecastle break investigated. Very little information given for this loading.	48.
					Ship deflections	Theodolite and 7 targets.	Theodolite and targets on upper and forecastle decks.		
				Ship in dock on piers loaded by known hogging B.M. to ultimate load	Strains, generally in rosettes	420 Acoustic gages 5 and 10 cm. G.L.	Transverse section amidships. Both sides of plating or one side plus another on button of known thickness.	Support reaction from piers applied to ship neutral axis. Ultimate failure due to buckling of bottom at stress (in keel) of 17 tons/in². Corresponding hogging bending moment at test section 125,000 tons ft. In instrumented side panel mean value of maximum shearing stress, 4.75 tons/in². vs. 4.09 calculated from beam theory for 548 ton shearing force increment. Up to moderately large bending moments, observed and calculated deflections agree closely with shearing deflection included. Measured deflection greater than calculated before any plate wrinkling observed and discrepancy increased with loading. No rivet slip therefore no allowance necessary for rivet holes in Ship I calculation. All longitudinally continuous material was fully effective. Simple beam theory gave correct values for mean direct stresses but slightly underestimated deck edge stress and slightly overestimated deck centerline stress.	
						15 dial gage type 13½", 15" and 100" G.L.	Transverse section amidships on deck and webs of longitudinals		
						100 Electric resistance gages 1/2" G.L.	Both sides of plating panel at ship neutral axis in region of high shearing force		
					Ship deflections	Theodolite and 7 targets	Theodolite on deck, targets on upper and Forecastle decks		
1951	CASCO	300' Coast Guard Weather Ship		Vessel at sea in North Atlantic. Some fairly heavy weather encountered.	Fore and aft strains. Random continuous record. Also strain cycle totals.	Electric resistance gages. Mechanical strain cycle gage, 10" G.L. Differential transformer gage 10" G.L.	Keel and two symmetrically located main longitudinals amidships and at quarter point forward.	Statistical methods used in analysis and normal distribution patterns found to apply. Vessel subjected to slamming during which peak impact pressures over 265 lbs./in.² recorded. Maximum stress variations; 4700 lbs./in.² associated with rigid body motion and 1400 lbs./in.² associated with flexural vibration on account of slamming. Rigid body stresses much smaller than anticipated from static wave calculation. Waves 330' x 16' encountered. Double amplitudes of pitch, up to 20°; roll, up to 37°. Longitudinal bending stresses at forward quarter point of same order of magnitude as amidships. Endurance strength under repeated loadings felt to be an important consideration in design.	55.
					Heaving, rolling and pitching accelerations sampled.	Electronic recorder			50.
					Random normal pressure loading	Differential transformer diaphragm	Bottom-well forward.		

A COMPARATIVE STUDY OF EUROPEAN WELDING OPERATIONS

ACKNOWLEDGEMENT

This article is a report of three United States members of a mission which spent four weeks visiting plants and conferring with welding experts in eleven European countries. It was published in the October, 1955, issue of "The Welding Journal." The authors were R. W. Clark, Welding Engineer of General Electric Co.; S. A. Greenberg, Technical Secretary, American Welding Society; and C. E. Jackson, Research Metallurgist, Metals Research Laboratories, Linde Air Products Co.

ORIGIN AND OBJECTIVES OF EUROPEAN TOUR

THE ORGANIZATION for European Economic Cooperation, commonly called OEEC, was founded by the Western European nations to provide a means for the free exchange of technical and economic information obtained in each member country. The United States and Canada are Associate Members.

The European Productivity Agency, EPA, is one of the divisions of OEEC, primarily concerned with providing information which will improve the economic status of European countries through increased productivity—that is, a more efficient, less costly manufacture of products. The program of EPA is largely carried out by experts or organized study teams. Through tours, visits and conferences in different countries, these experts or study groups survey the knowledge, experience and technical facilities pertinent to the particular subject or field of industrial application.

A few years ago a European study group, called a "mission" by EPA, visited the United States to study the welding practices followed in American industry. One of the recommendations of this mission at the conclusion of its visit was that a similar mission of Europeans be organized to tour European welding operations. This was deemed desirable in order to provide a basis of comparison between European and American welding practices. Acting on this recommendation, EPA Mission 250 was created to make a "Comparative Study of Welding Techniques in Europe."

Organization of Mission 250 was made much easier by the existence of the International Institute of Welding. Being an international affiliation of welding societies and institutes in different countries, IIW obtained the cooperation of each of these national welding organizations in the selection of qualified members for the mission and in the organization of visits and conferences by the mission within the different countries.

Since it was desired to compare American and European welding practices, as well as welding practices among European nations, invitation was extended to the American membership of IIW to appoint three representatives to Mission 250. The American Welding Society, as one of the three organizations sharing American membership in IIW, designated R. W. Clark and S. A. Greenberg, and Welding Research Council and Ships Structure Committee designated C. E. Jackson. In all, the 29 members of Mission 250 included representatives of fifteen countries as follows: Austria, Belgium, Canada, France, Germany, Great Britain, Greece, Ireland, Italy, Netherlands, Norway, Portugal, Sweden, Switzerland and United States.

OEEC Mission 250 met in Paris on Monday, April 18, 1955, and in the four weeks ending Saturday, May

14, 1955, visited plants and research organizations and conferred with welding experts in the following eleven European countries: Austria, Belgium, Denmark, England, France, Germany, Holland, Italy, Norway, Sweden and Switzerland.

There remains for Mission 250 the task of preparing a report of its tour with conclusions and recommendations as indicated by what was seen.

This is an interim report by the American members of the Mission prepared with a twofold purpose: To provide the American point of view for inclusion in the report of the Mission and to apprise those in American industry interested in the application of welding of what we saw in Europe. The final report of the Mission is expected to include the recommendations of the Mission. The conclusions at the end of this report were independently arrived at by the United States representatives. We believe them to be of particular interest to industry in the United States.

The tour of Mission 250 included visits to manufacturing plants; discussion with welding experts; inspection of fundamental and applied research programs; and the inspection of welded bridges, an oil refinery and a power station already in service.

DEVELOPMENT OF WELDING PROCESSES IN EUROPE

It must be considered that the plants visited by this Mission were representative of European practice. As in the United States, the selection of welding processes and techniques for any application is dictated by the product being fabricated, the equipment available, the regulations within a country, the type of labor available, as well as strictly economic considerations. In some of the installations the equipment available for a particular operation might not insure the most economical operation. However, since the cost of labor in Europe is generally low, the urgency for scrapping an existing production setup in favor of new equipment requiring additional capital expenditure is not always great.

It is interesting to note that the number of welding processes actually being used is large. A listing of the welding processes observed follows:

Arc Welding:

1. Carbon electrode, unshielded
2. Metal electrode, unshielded
   - (*a*) bare metal arc
   - (*b*) stud welding
3. Metal electrode, shielded
   - (*a*) covered electrode (short lengths)
     - (1) manual
     - (2) machine (firecracker / self-consuming / "stick feeder")
   - (*b*) covered electrode (coiled lengths)
   - (*c*) atomic hydrogen
   - (*d*) inert-gas metal-arc
     - (1) tungsten electrode with and without filler metal
     - (2) consumable electrode
   - (*e*) submerged arc
     - (1) single pass
     - (2) multiple pass

Resistance Welding:

1. Spot welding with
   - (*a*) portable guns
   - (*b*) single-spot machines
   - (*c*) multiple-spot machines
2. Seam welding
3. Flash welding
4. Projection welding

Thermit Welding (nonpressure)

Gas Welding (oxy-acetylene)

Forge Welding

Brazing:

1. Torch
2. Dip
3. Induction

The arc-welding machines are generally single-operator units with a high degree of portability. This is equally true for a-c and d-c welding. Single operator machines generally are of 300 to 400 amp capacity, although one shipyard installation consisted of twelve 900-amp generators. The largest single unit of power seen for heavy submerged arc welding was 15,000 amp. One application with multiple electrodes using very high currents (over 4000 amp) for submerged arc welding of heavy steel plate was observed. However, the usual power supply seen for submerged arc welding is 900 amp.

Light-weight readily portable oxygen-cutting equipment is widely used for straight line plate preparation and convenient accessories are used for manual shape cutting. Other installations seen for plate preparation include elaborate multiple torch machines with template control. Multiple torch setups are also used for plate edge preparation of special bevels. An "electronic eye" control unit was seen used in a few installations. Practically no stack cutting was noted. While some use of propane was noted, acetylene is the most commonly used fuel gas.

The speed of welding seemed to be generally slower than in the United States. Some of the positioning and handling equipment seen was outstanding. We estimate that over 90% of the welding observed was done downhand. Equipment for mechanically feeding covered electrodes from a magazine was used to an advantage in a few specific applications. A machine welding process using continuous coils of covered electrode was seen used frequently for long multiple pass seams. Auxiliary equipment, such as cables and electrode holders, is much like that used in the United States.

As in American practice the most widely used process is manual metal-arc welding with covered electrodes. Submerged arc welding is used extensively in welding plate and longitudinal and girth piping seams. Three applications of a process known in the United States as "firecracker welding" were observed. To us, it appeared that this process was slow

if considered in the light of other available machine-welding processes. A fair number of applications were noted using a continuous, coated electrode and several applications were noted where mechanical equipment for feeding manual covered electrodes was used. This last process was used in at least one application with regular short lengths of a low-alloy steel covered electrode to obtain improved low-temperature properties in the deposited metal. Inert-gas metal-arc welding using a tungsten electrode was seen used, either with or without filler metal, in those few instances where we saw the welding of aluminum. Argon is used exclusively since helium is not available in Europe. On the basis of initial experiments interest is developing in the use of the consumable electrode method for welding aluminum, although only two applications were noted on this tour. No application using submerged arc welding of steel sheet metal was observed.

In general it can be said that the welding techniques employed in Europe compare favorably with the standard practices used in America.

LABOR AND MANAGEMENT

Labor costs in Europe are low and material costs are high when compared to the United States. As an example, a Director of a German company stated that the saving of one ton of steel justifies the use of up to 80 man-hours of labor. Before the war this ratio was 1 to 40 in Germany. He gave a ratio of 1 ton to 20 man-hours in the United States as his figure for comparison. He further stated that this situation favored lightweight design and the use of welding. By this approach this company realized a material savings in a medium-sized harbor crane of 15 to 20% in 1944 over 1924. In a 1955 design another 40% has been saved.

In all of the eleven countries we visited, employment was high. Welding is used very extensively to save steel as well as to reduce weight. A great deal of time is spent in design and planning. It is common practice to use sheet and plate fabricated into shapes best suited for each structure by oxygen cutting, forming and welding. Management appears to be fully aware of the importance of quality control in welding applications.

Generally, supervision of welded construction is handled by technically competent welding engineers and welding supervisors who have been trained in both the practical and technical phases of welding (mainly arc and gas welding). Generally the workmanship is good indicating proper control of all factors involved in the applications of the welding processes. European industry is fully aware of technical developments in welding applications in the United States.

Welders are generally paid by the hour or on an individual piece-work basis. There is very little use of group incentive systems. In some plants bonuses are paid quarterly or yearly based on output or earnings. It appeared in general that rather narrow ranges of extra pay are used for efficiency. When considered as incentive plans to increase productivity, the European plans we encountered do not appear to us as effective as many of the incentive plans used in the United States.

It is very common in Europe for all tradesmen to have apprentice training, including both schooling and practical training, and to pass tests before becoming qualified to practice their trade. Generally this practice applies to welders also. It is also very common to retest welders every two years. The welders' tests are basic tests used for screening purposes.

Industry in Europe appears to recognize that the broad aspects of using welding involve suitable design, manufacturing processes and quality control. There are many countries where industry has sponsored and supported laboratories and institutes which assist in solving their problems with application of the welding processes.

An example is the Central Welding Institute of Denmark which does X-ray inspection of welded joints in each sponsor's plant twice a year without advance notification. Production welds made by each welder are X-rayed and all welders are classified. A running record of all welder classifications is furnished the manufacturer. Also as they find welding of questionable quality they determine the cause—which may be the welder, material preparation, assembly or design—and inform management accordingly.

The many institutes of welding in Europe are not promoting joint welding procedure qualification as such but rather assisting industry in the application and control of all factors involved in the application of a welding process to specific applications. They question the great emphasis placed on welder and procedure qualification in the United States and our lack of consideration of other factors involved in the application of welding.

These institutes also assist industry in the interpretation of codes, such as ASME or ABS, which is not always simple. They also evaluate new welding equipment and processes when requested.

While one of the main purposes in using welding in Europe is to conserve material, at the same time by proper design and quality control they have also obtained reduced product cost.

HEALTH AND SAFETY

Health and safety in welding are of far less concern in Europe than in the United States, assuming what we saw and those with whom such matters were discussed are representative.

In only few shops are ducts used for exhausting the air at welding stations. However, a majority of the shops seemed to be free of fumes and smoke, adequate ventilation being provided by the natural flow of air.

Fumes are of little concern but this is probably due to the fact that the greatest amount of welding by far is done on carbon and low-alloy steels with gas welding, shielded metal-arc welding or submerged

arc welding. In one shop where inert-gas metal-arc welding was in progress, ozone was present in sufficient quantity to be mildly irritating.

Except in one plant visited, there was no use made of curtains or screens to shield nearby workers from the rays of the arc. It is common to see one welder cleaning a weld in very close proximity to the bright arc of another welder making a weld.

The welders themselves, of course, use eye protection during welding. For gas welding and cutting, goggles are used, much like those used in the United States. It is interesting to note, however, that for shielded metal-arc welding, hand shields seemed to be preferred over helmets in all the countries visited except Norway. Both helmets and hand shields were seen used, sometimes in the same plant, in Denmark and Switzerland. Where nonconsumable inert-gas metal-arc welding is used, a changeover to helmets has been necessary.

A general preference is indicated for d-c welding over a-c welding in all countries except Sweden. This was explained on the basis that the shock hazard with d-c is less than with a-c. In Germany, government regulations actually prohibit the use of a-c for safety reasons in pressure vessel fabrication and shipbuilding, the two industries covered by government standards.

Oxygen cutting operations, almost without exception, are done with a far greater rate of oxygen consumption than is normal in the United States. Contrary to safety recommendations in the United States streams of sparks flew in all directions and for considerable distances. Comment on this on several occasions did not seem to arouse the concern of anyone.

Inert-gas metal-arc welding is only just beginning to be used in most European industry and the safety aspects of this process have been given little consideration to date. A study has begun in England under the sponsorship of the British Institute of Welding and in this connection there was interest shown in the study completed by the American Welding Society last year.

Welders seem to be clothed in a manner which would conform to American standards of safety, with long sleeves, heavy shirts, heavy shoes and cuffless trousers.

An interesting device for detecting the presence of gases in an atmosphere was demonstrated in Germany. This seemed to be a good means for checking the contents of a container or tank which had previously held combustibles and was to be welded or cut. The device consists of a bellows by means of which an air sample is drawn into a glass tube. The glass tube contains crystals of a chemical which changes color in the presence of a specific gas, different tubes being available for different gases. Each tube is graduated and the proportion of the gas under question present in the air sample used can be read directly.

On the whole welding shops were unusually clean and orderly by United States standards, minimizing the possibility of fire.

Very little evidence was seen of safety posters or any special awareness of the need for safety. First-aid kits were practically nowhere in view.

STANDARD SPECIFICATIONS AND QUALITY CONTROL

European standardization activities are following a pattern closely comparable to the earlier experiences with standardization in the United States. Standards are being developed as the need for them is indicated. Currently the need appears to be greater and the standardization activities have increased accordingly.

Such standards as do exist are seriously lacking in uniformity from one country to another. However, steps are being taken toward effecting agreement through OEEC activities and through such organizations as the International Institute of Welding and the International Standards Organization of which Technical Committee 44 deals with welding.

New standards will probably be more uniform because of these organizations and because their activities will provide a means of interchange of ideas between participating countries, much like AWS and the other national welding organizations provide within their respective countries.

At present standardization is most extensive in those industries where the government is the prime customer. Railroads, shipbuilding and bridge construction are the most notable examples. Standard specifications in these fields vary as to the extent of detail. In many cases they are detailed purchase specifications; in other cases the specifications or standards are broad basic definitions of design, material, fabrication requirements and inspection.

The following itemization of standards in the countries visited is by no means complete. It represents only that information which was obtained by the American representatives during the trip.

In France, government specifications or standards cover the fabrication of bridges, railroad equipment, pressure vessels and ships. These are prepared by commissions serving under a government agency. The French Institute of Welding is represented and cooperates in these activities. It also issues some recommended industrial standards of its own.

In England there are recognized industrial standards apart from those issued by the British government for its own facilities. These are issued by the British Standards Institution, with the Institute of Welding cooperating in their formulation.

In Germany, the Deutscher Normenausschuss issues the well-known "DIN" (Deutsche Industrie Normen) standards for different industries. Such DIN standards are available for pressure vessels. As in other countries bridges are built for the government and made under government specifications.

In all other countries visited no information was obtained to indicate the existence of standard speci-

fications, except for government purchase as previously mentioned.

As in the United States, the larger companies in Europe formulate standards of their own for purposes of quality control. Where standard specifications exist, these company specifications are in agreement with them.

Base metal requirements are not usually covered by standard specifications. Steel is purchased on the basis of mechanical properties, chemistry, trade name or a standard means of identification.

Electrodes are covered by standard specifications in Germany for bridge and building construction. Industrial standard specifications for electrodes are widely used in England. In other countries it appears to be the general policy to use electrodes of a given brand with little or no interchangeability. In only one instance, in France, was there evidence of a familiarity with United States standards. This plant was engaged in the fabrication of pressure vessels for an American customer under the API-ASME Code for Unfired Pressure Vessels for Petroleum Liquids and Gases. This company also follows the ASME Boiler Code.

Probably due to the absence of general industry standards, quality control, it was found, is usually based on practices established by each company. Greater stress is placed on design, workmanship, training and supervision, with less emphasis on metallurgy and qualification than in the United States.

Joint welding procedures were used as established by a company's engineering staff and qualified for its own information rather than to meet regulatory requirements. The same is true of inspection and testing of finished weldments, although in some cases such inspection is prescribed by the customer.

In general the test methods used are similar to those used in the United States for similar applications. In structural welding, for example, visual inspection is usually considered adequate. For pressure vessels and piping hydrostatic and air pressure tests are used, the test pressures being one and one-half or two times the design pressure. In this field radiography is also used extensively. In addition to X-rays, all of the available isotopes, including radium, cobalt 60 and cesium 137, are used for radiography in different plants. One plant in England had all these sources.

The use of ultrasonic waves was being studied in Britain and France. These studies include the use of a single probe for weld inspection. In only one plant, in Switzerland, was actual use being made of this process for weld examination. This company has developed a method using a single probe and a specially designed template by means of which a weld defect can be readily located when detected.

For resistance welding, in the fabrication of automobile bodies and railroad car sides and roofs, the peel test is used by one company and the tension-shear test by another. As in the United States, these tests are made at prescribed intervals, such as the start of each day, as a control on the machine settings and operation.

Spot weld appearance seemed to be of less concern than it is in the United States. This is probably due to the more usual use, in Europe, of painted mild steel rather than stainless steel or aluminum for railroad cars. Welds on automobile bodies showed equal amounts of indentation or excessive burning, but were not as conspicuous in the finished car, many of the seams being obscured by moldings or the configuration of meeting parts.

There was ample evidence to indicate that European industry is fully cognizant of all factors involved in quality control. The judicious use of quality control measures is well demonstrated by the general high level of weld quality observed.

PRODUCTIVITY

Many new, rebuilt or modernized plants have been planned with material-handling facilities and processing equipment for line production similar to plants in the United States. We were impressed by the fact that the European countries have up-to-date technical knowledge and experience in applying arc- and gas-welding processes. Should it be necessary to meet the market demands for their products either at home or abroad there is the know-how in Europe to effect labor saving and make greater use of automatic equipment. To what extent European productivity is increased will depend on economic conditions in each country and the world.

TRAINING OF WELDERS IN EUROPE

In most of the countries, programs for training and qualifying welders were described. In many of the countries training is sponsored and directly supported by industry. Apprentice training is a part of most fabricating shops, with training varying from two months up to five years. In the three- to five-year programs, an extended period of shop service is associated with the actual training. In England, one company estimates that it costs $100 per week to train a welder in a plant, including salary. Indoctrination of all new welders, and welders used on new applications was generally observed. Use is made of symposiums, panels and regional technical meetings for distribution of information to engineers and other interested personnel. One college course was described which provides a class in welding engineering as part of a course in mechanical engineering.

In France, the Institute de Soudure has organized a training program for welders and supervisory personnel. This organization presents a course which leads to a professional certificate. The regular training courses are under the guidance of the National Education Ministry; shorter courses, of one week to two weeks' duration, are arranged at the request of industrial concerns. The cost of instruction in this case is partly paid by the student or his sponsor, the balance being paid by government funds. The three-year course includes studies in physics, chemistry,

electricity, mechanics, metallurgy, mathematics, as well as design and practical welding. Other courses, of one week to two years' duration, are provided for welders and other artisans who wish training in welding.

One French plant has twenty welding stations for training welders. This is operated for two shifts and continued for three to four months. Another plant give specialized training based on an American text, and continues this training for approximately two months, after which the men who qualify are given further instruction while being used on the job as tack welders.

In England, extensive apprentice and on-the-job training is provided by industry. This is coordinated, through the British Institute of Welding, with the activities of the City and Guilds of London Institute.

The training of welding engineers is the subject of a current study by the British Institute of Welding. For the most part today. welding engineers are civil, mechanical or electrical engineers who have specialized in welding in industry. The British Institute of Welding is active in getting the universities and technical colleges to include welding courses in their curricula. A conference is being planned for 1956 on the place of welding in technical education which will consider the role of the welding engineer in industry, the type of education required by a welding engineer and the means of providing such education within the present educational system.

In Norway and Sweden apprentice systems have been set up giving training in various plant operations to the workmen. These activities include training in welding.

In the Netherlands, welders are trained in one plant by instruction on the job. Selected men are given a minimum amount of training and then used on minor jobs and for tack welding, until a proficiency in welding is developed. The Netherlands Welding Society also conducts training courses for welders and engineers.

In Germany, welders are trained in the plants, with a certificate being issued to those qualified by German Lloyd's or Technischer Uberwachungs Verein, depending upon the type of work being performed. The Schweisstechnische Lehr-und Versuchsanstalt and other industry-supported schools also train welders in Germany. There are four or five such schools in different parts of Germany. Students are usually sent to the schools by industry, who pay the fees and expenses of the students. Training is also provided for upgrading of the workmen.

In Austria, the Central Institute for Welding Technique is mainly interested in the training of welders, welding foremen and welding engineers.

In Italy, the largest number of welders are instructed and examined by the plants themselves. Schools at Milan and Genoa hold classes four evenings each week for six months, giving 100 hours of theory and 80 hours of practical welding. At the end of the course, a special commission, including state representatives, examines the students. When qualified, the student is given a certificate of specialization in welding. The welders for various industries, such as shipbuilding, are examined and their qualifications noted by a special board.

In line with the general policy of apprentice training in Europe, it was our impression that more consideration is given to training welders in Europe than in the United States. The same can be said for the training of welding engineers and foremen.

RESEARCH IN WELDING

Most of the research work in welding in Europe is closely associated with improvement in use of the welding processes or of welding techniques, rather than with fundamentals. As might be expected, research in the different countries is unrelated. It seems best, therefore, to report on the research facilities in the order in which they were visited.

At the Institute de Soudure in Paris we saw the following studies, among others:

Metallizing with aluminum on rimmed steel plate to reduce porosity during inert-gas metal-arc welding. Approximately 0.30% aluminum appears to be sufficient according to their latest fiindings.

Use of a hot air torch for the welding of plastics. A polyvinyl plastic was being studied.

A weldability program using the Kinzel test at a temperature of —60° F. Present studies are confined to base metals.

At the Manchester College of Technology, in England we saw studies involving

Damping of welded structures
Lattice column design
Influence of oxygen cutting for edge preparation on fatigue of weldments
Photoelastic studies of design variations
Fatigue of heavy welded chain

The activities of the British Welding Research Association are carried out in two laboratories, one at London devoted mainly to metallurgical studies and the other at Abington (near Cambridge) where we saw

A fatigue program intended to evaluate the behavior of butt joints in structural members. A 100 to 200-ton machine was being used to apply a pulsating tensile load to steel plates ½ to 1¼ in. thick. Similar testing is being performed on welded piping. Confirming previous findings in the United States, the results thus far show the importance of geometry of the test specimen on its fatigue behavior.

The usefulness of tri-form or collar reinforcements in Y-connections is under study for heavy wall pipe of 8-in. diameter. The stress is determined in the welded joints by means of SR-4 strain gages

In a study of brittle fracture, a number of different types of test specimens are being investigated, including a repetition of Doherty's large-scale bend test.

Other programs of investigation include the efficiency of oxygen cutting; potential use of ultrasonic equipment for weld examination; instrumentation for resistance welding.

In addition to a number of development and control problems in connection with the manufacture of

electrodes, research is being carried out in two fields at Elektriska Svetsnings A.B. in Sweden:

Brittle fracture under tensile loading using a specimen with a castiron weld deposit along both edges as a crack starter.

A special hardenability test using a high-frequency unit for heating and a water bath for cooling a small specimen at a rate similar to that encountered in the heat-affected zone during an arc-welding operation. By such test it is possible to measure one of the important factors in evaluating the weldability of a steel.

At the University of Ghent in Belgium we saw several programs under investigation:

Brittle fracture in a large-scale test piece with a biaxial load being applied on a 800- x 8-in. test section. In the cruciform-shaped test piece three of the stressed corners are heated by small torches to prevent failure. The fourth corner is cooled by liquid air to the desired temperature to control the location and nature of the failure. The type of fracture and the propagation of brittle failure are a measure of the properties of the steel. Many Robertson's test pieces are being studied for reference.

Fatigue behavior of welded rails is being studied under simple beam loading. Additional fatigue testing is under way.

At the Association des Industriels de Belgique in Brussels two large testing machines were of interest.

The first of these is a horizontal compression-tensile unit with a specimen length of 65 ft. (20 meters). The capacity of this unit is 1000 ton compression and 800 ton tension. The second testing machine is used for fatigue testing a welded cross joint of 16-in. I-beams. The capacity of this unit is 100 ton in vertical loading and 50 ton in all other directions.

WELDING SOCIETIES AND INSTITUTES

One or more welding societies or institutes were found to exist in every country that was visited. The size and functions of these organizations are quite varied. Briefly, this is a report of these institutes in the countries visited in so far as informtaion was obtained.

In France the Institute de Soudure, with a staff of 130, conducts training programs for welders and supervisory personnel, does field inspection of welding on a fee basis and conducts research for product or process development with support from a single company or an industry. It issues a magazine every two months and a series of technical manuals on different welding subjects. A library service is maintained and translations of welding standards, periodicals and articles prepared. Standardization activities are not carried out directly by the Institute de Soudure, but this organization serves in an advisory capacity in this work.

Entirely apart from the Institute de Soudure is the French Institute of Welding Engineers, an individual member society which holds regular technical meetings and engages in other professional engineering activities.

In Britain the Institute of Welding functions as an individual member organization, with a written test required for admission in addition to specific entrance requirements. This Institute has a technical division which maintains a library service, issues a monthly magazine and cooperates in the establishment of training standards for welders. It engages in activities of professional interest, such as the training of welding engineers in colleges, and cooperates with the British Standards Institution in the formulation of standards on welding. Welders are admitted to membership in the Institute according to qualifications established by the City and Guilds of London Institute for the classification of a welder.

The British Welding Research Association was formerly a part of the Institute of welding but is now operated separately, with close cooperation between the two organizations. Unlike its American counterpart, Welding Research Council, BWRA receives contributions from industry only to its general fund. Research programs are organized and followed by committees with all funds for such work allocated from the general fund.

Of interest in passing is the British Electrical Manufacturers Association, BEMA, which is active in the standardization of electrode classifications.

The Norsk Sveiseteknisk Forening (Norwegian Welding Society) was started in 1932 but has employed a full-time secretary only during the past year. It has begun to issue a regular magazine and work is now under way in the preparation of up-to-date By-Laws defining its operations.

No information was obtained in Sweden concerning the activities of the Svetskommissionen.

In Denmark, the Danish Institute of Welding, DSL, has 400 active members and holds regular technical meetings. The Central Welding Institute of Denmark is a nonprofit organization sponsored by industry for inspection of welding.

The 6000 members of the Netherlands Welding Society are divided into thirteen departments (local sections), one in each province. These members include welding engineers, technicians and welders. A journal is issued regularly and one of its principal activities is the establishment of training courses for welders and teachers of welding. Only recently a Netherlands Welding Research Center has been organized to carry out welding research programs.

In Belgium, in addition to L'Institut Belge de Soudure (Belgian Institute of Welding), there is the Association des Industriels de Belgique, which performs inspections and conducts research programs in welding and many other industrial matters on a fee basis as requested by a company or industry.

In Germany, the welding organization is known as the Deutscher Verband fur Schweisstechnik, with headquarters in the heart of German industry at Dusseldorf.

The welding organizations in Austria interested in welding include Schweisstechnische Zentralanstalt (Central Institute for Welding Technique); Oesterreichischer Gessellschaft fur Schweisstechnik (Austrian Association for Welding Technique); Oesterreichischer Normen-Ausschuss (Austrian Standard Committee) and Oesterreichischer Stahlbau-Verein

(Austrian Association for Structural Steel). A monthly publication is issued jointly by the first two of these organizations.

The Central Institute for Welding Technique concerns itself mainly with the training of welders, welding foremen and welding engineers. This Institute also acts as a consultant to industry and by lectures and demonstrations keeps the smaller companies informed of the latest developments.

The Austrian Association for Welding Technique is essentialy a member organization.

The Swiss Acetylene Association and the Society Suisse de Constructeurs de Machines are the two organizations in Switzerland mentioned with respect to welding activities.

In Italy the arrangements for the visits of the mission were handled by the Institut Italien de Soudure, but time did not permit procuring information concerning the activities of this organization.

It is obvious from the foregoing summary of welding organization activities that the information obtained is far from complete. This report is based on information gleaned as occasion provided, either through conversations with staff personnel or members of these organizations or from literature provided. It is important to note that the extent of coverage in any case is not necessarily an indication of the extent of the activities of that organization. We expect that the complete report of the Mission will provide the missing information.

One other fact was apparent in this connection. Each of these organizations is active in the International Institute of Welding. Through IIW the efforts of all these national welding organizations are correlated for the dissemination of joint reports on subjects of mutual interest. Through IIW they also influence the standardization activities of Technical Committee 44—Welding, of the International Standards Organization.

AUTOMOTIVE PRODUCTS

The extent to which welding is used in the manufacture of automobiles in Europe differs primarily in the rate of production. The number of welding processes used is large. Where the rate of production is as small as 1000 cars per week there is less use of automatic welding and more handling of the work. Where there is a high rate of production, as in Italy where 800 cars per day are being produced, use is made of automation and mechanical handling.

Plants making automotive products were visited in France, England and Italy. Almost all of the welding processes used in the United States are in use in these European plants. To cite some examples: Bare carbon arc welding is used for automobile frames in one plant; shielded-metal-arc welding in others. Manual shielded-metal-arc welding is used for body assembly and for the attachment of miscellaneous fittings and brackets. Because of the lower production rates this process is used for body assembly to a greater extent than in the United States. This is not to say that the more usual United States practice of using spot welding is not followed. As a matter of fact the Italian plant had multiple spot-welding machines which make up to 50 welds per assembly.

Much like in the United States flash welding is used in the Italian and French plants for fabricating rear axle housings. Use is made of this same process for joining two formed halves of a wheel rim. One plant in England uses manual metal-arc welding for welding rear axle housings. Another plant in England uses a machine welding setup by which welds on opposite sides are made simultaneously using coiled, covered electrodes. In all cases extensive jigging is used to align the parts and position the work.

Seam welding is used for making gasolene tanks, but the rate of welding is much slower than the 800 in. per min. achieved in one automobile plant in the United States. In one plant visited induction brazing is used to attach fittings to these tanks.

All of the above-cited applications involved the use of a low-carbon steel. However, in a French plant automobile bodies are being fabricated of aluminum using inert-gas metal-arc welding.

RAILROAD CARS AND MAINTENANCE

Railroad car and locomotive builders were visited in France, Belgium, Netherlands and Norway. The shops of a railroad were visited in France.

Rails up to 800 meters (2625 ft.) in length are being flash welded in the shop. Thermit welding is being used in the field to make continuous rails, similar to the practice followed in the United States. In France passenger cars of stainless steel are being built following American practices very closely. In some of the other countries passenger cars are made of mild steel. The main structural members are manually arc welded and the car sides and roofs are resistance welded to the frame. Far less attention is given to avoiding indentation and surface marking since in the course of painting such markings are eliminated.

In Belgium one plant is fabricating diesel locomotives according to an American design. Another Belgian plant is making railroad passenger cars using steel for the framing and aluminum for the sides and roof. Seam welding and inert-gas metal-arc welding using a non-consumable electrode is used. For joining the roof a filler metal which is formed to serve as a backing as well is used. This is similar to filler metal introduced for welding stainless-steel piping about a year or so ago in the United States.

The plant in the Netherlands makes both locomotives and passenger cars. Processes used include shielded-metal-arc welding and to a lesser extent submerged arc and spot welding. Submerged arc welding was being used on metal 0.20 in. (5mm) thick. This is the thinnest material we saw being welded by this process. Production in this plant is at a rate of twelve passenger and freight cars per week.

As much from riding in European coaches as from visiting these plants, we were impressed with the fine styling and craftsmanship of these cars. Much of the

rolling stock is excellent, with quiet operation and smooth performance.

SHIPBUILDING

In Europe, all the shipbuilding yards which we visited were busy. The practices and techniques of ship construction, in general, were similar to those used in America. Extensive use is made of oxygen cutting equipment for plate preparation, together with modern automatic submerged arc equipment and a weldable steel.

In Sweden one of the largest yards was visited. Much of the yard is new, with new shops and increased acreage being obtained during the past decade. Production in the new yard begins in a plate shop with equipment and space fitted for work on plane plates, curved plates, profiles and framed sections. These plate shops are convenient to the welding shop, where the pieces are joined into sections weighing up to 40 tons. Shop welding is largely done by the automatic submerged-arc welding process. The welding shop is adjacent to three concrete berths, each capable of accommodating hulls up to 35,000 tons dead weight. The use of prefabricated sections speeds up the assembly on the berths so that an 18,000-ton tanker requires a building time on the way of three months or less, using manpower on only one shift. Welding on the ways is done with stick electrodes, either manually or by machine welding.

In Denmark, the mold loft of a shipyard we visited uses a large-scale projection of the drawings from which the sections are directly laid out on steel plate. Films with carefully scaled drawings are used in a very large projection room, and the lines on the plates marked with a punch without any further scribing. Heavy shearing equipment permits high-speed bevel cuts being made in 40 ft. long, 1-in. thick plate. Automatic submerged-arc welding equipment and improved handling facilities reduced the labor in this yard to approximately 180 man-hours per net ton of steel in a tanker or cargo vessel.

In the Netherlands, a yard was visited which had 6000 employees. Much of the plant construction is new, having been built after the last war. The capacity of the yard has been increased from 15,000-tons before the war to a present size limit of 27,000 tons. Automatic submerged-arc welding is used in the shop assembly of plates. In order to improve the safety of the service of some of their vessels, a proprietary low-temperature steel is being used in certain critical midsection areas.

One of the smaller yards visited in West Germany is probably typical of such yards in Europe, having 450 employees of which 50 are welders and 32 salaried personnel. Eighty percent of the effort is directed toward new work and 20% to repairs. In 1946 this yard scrapped all riveting equipment so that future work would be carried out entirely by welding. It was stated that this conversion was made in spite of the fact that at first the cost of welded construction was higher than for the previous practice of riveting. All welding in this yard is manual since they do not have confidence in using the automatic processes in construction carried out in an open yard. No shelter is provided for any of the construction in this yard. Tankers up to 1400 tons are being built. The yard has 15 berths and a special side launching setup which provides ready launching of the small ships into the water.

In an Italian yard, it was stated that they began using arc welding in ship construction in 1927. Welding has continued to be used since that date in order to give them lighter structures. This particular yard uses approximately 135 tons of steel per day, and has a total of 4800 employees. A very unusual handling system with overhead cranes on overhead cables gives this yard flexible control in a space 682 ft (210 meters) wide, 975 ft (300 meters) long and 221 ft (68 meters) high.

Machine welding is performed with a minimum of protection from the weather. A very elaborate installation is used for mechanically cleaning plate surfaces by blasting. Prefabrication of parts is done for about 80% of the construction of vessels in the range of 25,000 to 31,500 tons dead weight.

One of the oldest yards in France was visited. Large tankers were stated to be built at a cost equal to that of the Swedish yards (about $130 per ton). The claim was made that oxygen cutting and welding permit a small yard to become a large yard. This yard, it was stated, welds 90% of a tanker in the flat position. Automatic submerged-arc welding is used in an open yard with no protection from the weather. Flame cleaning is used immediately prior to painting. Sub-assemblies are made in spacious shops available for plate preparation and automatic and manual welding. A 90-ton field crane is available for use in assembly of the prefabricated sections.

The use of welding in the shipbuilding industry in Europe is firmly established. All the shipyards visited have extensively and carefully applied the techniques of welding. The extent of the use of automatic submerged-arc welding ranges from zero to more than 60% of the completed structure. The extent of preassembled shop welding ranges up to 80%. The materials used consist of low-carbon, killed steels, which reflect a practice aimed at greater resistance to brittle fractures. Since 60% of the steel made in Holland, for example, is used in shipbuilding, the steel can be more closely produced specifically for shipbuilding than is possible in the United States.

MACHINERY FABRICATION

Very extensive use of welding in machinery fabrication was seen in England, Norway, Denmark, Belgium, Germany, Austria, Switzerland and Italy. It is evident that the high cost of steel and a low labor cost are very important factors in this extensive use of welding in fabricated structures throughout Europe.

It appears that in general the carbon steels used in these welded structures have a lower carbon content than similar steels in the United States, the carbon

content being 0.23% max in Europe as compared to 0.30 to 0.35% max in the United States. Except for light-weight and low-stressed structures, where rimmed or Bessemer low-carbon steel is used, either aluminum or silicon killed open hearth or electric furnace steel is generally used. European silicon killed steels contain from 0.25 to 0.35% silicon as compared to 0.15 to 0.30% in the United States. In Austria, the oxygen process, basic Bessemer steel, is being promoted for welded structures. In all of these steels there is a tendency to keep the carbon under 0.23% and use manganese in a range of 0.90 to 1.00% to maintain minimum mechanical properties.

Low-alloy steels are used for fabricating steam turbine rotors and gears. These contain 0.23% carbon max and up to 1.5% manganese and 0.25% vanadium.

On heavy, important machinery structures, basic (lime-covered, low-hydrogen) electrodes are being used very extensively. In some cases these electrodes are being used for the first pass of fillet welds and in other cases for the entire weld. This type of covering is used in all cases that we saw involving alloy steel electrodes.

Very extensive effort is being applied to design to reduce weight and conserve steel. Formed sections from sheet or plate are used, with extensive use of stiffeners in all machinery. This is particularly true in the plants visited in Germany and Switzerland. As an example, in Germany Bessemer converters and electric furnaces are being fabricated with radical changes in design. In Switzerland and Italy steam turbine rotors are being fabricated of small forgings welded together because of the cost and weight limitations of large forgings. This type of construction also permits the use of more than one steel composition in the same rotor based on temperature requirements for specific parts.

In Italy, welded gears for marine applications are made using carbon steel for the web and a manganese-vanadium alloy steel for the rim. Small castings are used to advantage in fabricated structures. such as bearings used in gear casings and fabricated turbine casings. A stress-relief heat treatment is used only where dimensional stability is required.

In Germany, one company stated that all of their welded designs are checked to insure that they will meet service requirements by stress analysis and by load testing using strain gages. This method has assisted them in producing very light-weight structures, thereby saving steel and reducing the total weight of the product. It is interesting to note that this effort to save steel has, at the same time, resulted in lower total product cost.

While manual shielded-metal-arc welding is used very extensively there is evidence that mechanized welding processes are being applied where it is practicable to position and rotate the work. Practically no semi-automatic welding processes were seen in use. Submerged-arc welding, both single and multiple pass, appears to be used most extensively. Multiple-pass submerged-arc welding was seen used in welding alloy steel turbine rotors in Switzerland. A similar application involving only one welded joint per rotor is welded manually in Italy. The mechanized arc-welding process using continuous coiled covered electrodes is also being used quite extensively in one or two plants where production is limited or alloy steels are being welded.

Mechanized oxygen cutting is being used extensively in plate preparation and shape cutting. While manually guided torches and mechanized single torches are used and produce good edges, there is considerable use of multiple torch machine oxygen cutting for shapes and edge preparation.

Based on what we saw our impression is that management has a full appreciation of the importance of quality control. There appears to be a very effective follow-through in manufacturing to insure that material preparation, assembly as well as actual welding conforms to the design requirements. The use of non-destructive tests for quality control depends on the service requirements of the product. Such tests appear to be used not only for final inspection but to assist in supervision and quality control during fabrication.

Visual inspection was the most extensively used non-destructive test but we saw some magnetic particle and liquid penetrant testing of welds in marine diesel frames, turbine rotors and welded gears. While radiography was not being used very extensively for machinery fabrication, it was used in a number of applications for quality control purposes.

It is our impression that workmanship in manual welding is generally better than in the United States. The lower cost of labor and a fuller consideration of quality control may partly account for this.

Very little, if any, difference was noted in workmanship in the application of mechanized welding processes. As in the United States, in some plants emphasis is placed on keeping weld reinforcement to a minimum. In the machinery fabrication we saw, the preparation of material and the control of setup during assembly were held to a very high standard and again are better, on the average, than would be found in the United States.

A great deal of time is spent handling materials manually. However, there is evidence of great improvement in this area, even in the older plants. The new plants are well planned with very good crane facilities. Jigs and fixtures are being used very extensively. They appear to be able to extend the use of these facilities and reduce the labor content when and if required by economic conditions.

In Denmark, a plant fabricating diesel bases and frames is using large motor-driven positioners to position complete assemblies for manual metal-arc welding. Rotors in Switzerland and Italy are positioned for mechanized welding. In Germany where they are fabricating Bessemer convertors and electric furnaces there was very little positioning because of the size of

the assemblies and in this case there was considerable manual welding in the vertical position.

The high cost of steel and the lower cost of labor in Europe as compared to the United States have resulted in very extensive use of welding for fabricating machinery. This has resulted in products of lower weight, which is an advantage in many cases from the standpoint of power required in service as well as in the handling during production. Furthermore, use of welded designs has generally reduced the over-all cost of the product. It appears that Europe is very effectively applying their know-how in fabrication by welding to produce high-quality machinery structures which are competitive with the United States.

STRUCTURAL STEEL

Welded structures comprising buildings, bridges and handling equipment such as cranes, derricks, shovels, etc., were inspected in service or during fabrication or discussed with welding experts in Belgium, Germany, Holland, Italy, France, Austria and Norway.

In bridge construction the general practice has become to shop weld using riveting or field welding for erection, according to the specific experience and economic considerations of the particular fabricator. Railway bridges, like in the United States, are not usually welded, although strengthening and repairing, probably by necessity, are more usually by welding.

Among the notable examples of welded highway bridges inspected were three which span the Seine River near Rouen, France. The Point de L'Arche Bridge located at the junction of the Seine and Eure Rivers is 1100 ft. (368 meters) long, said to be the longest continuous span in Europe. The second bridge in the group is the Pont Corneille Bridge located in Rouen. It is a continuous arch bridge of two equal spans with a total length of 930 ft. Nine box girders are used to provide a four-lane highway bridge. The steel used is of fully killed open-hearth quality with a chemistry of 0.16 C and 0.50 Mn max., the tensile strength being 55 to 70,000 psi. The construction appears to be massive for the type of loads carried, but in the course of examining European bridge practices, it was found that there is a preference for thinner and shallower members and use of a greater number of girders with rather common use of box-girder sections for heavy bridges. Thicknesses of 2 in. are uncommon and could be considered maximum as compared to the use of flanges of 2 in. or more in the United States. (Four inches maximum is permitted in the AWS Specifications for Welded Highway and Railway Bridges, although it is considered preferable to use a flange and cover plate rather than a flange thickness of more than 2 in.)

The third bridge in this series is called the Jeanne d' Arc Bridge and is now in the course of erection. It comprises seven box girders each of 650-ft. continuous span length. The steel used is the same as for the other two bridges. In all three cases erection is by field welding.

Unfortunately no information was available on the design of these structures, nor on the allowable stresses used. In the instance of the Pont Corneille Bridge it was reported that the cost was $240 per ton (90 fr/kg) as compared to an estimated cost of $272 per ton (103 fr/kg) for a riveted design.

In Germany, a number of bridges were being replaced over the Rhine River in the Düsseldorf-Duisburg area. These were in the nature of sections fabricated from plate by welding and assembled by riveting. The fabricator claimed this procedure to be most economical on the basis that it eliminated joint preparation and careful fit-up of members in assembly. No bridge work was seen in progress in this plant, but the impression was gained that needless forming was being done, as in the flattening of angle members joined to the chords of a crane girder where clearance did not seem a problem. It appeared that welding the heels of these angles directly to the chords, without flattening (as is done in a plant visited in Holland), would have been equally satisfactory and would require less forming.

No welded bridges were seen in Belgium, but in discussion it was reported that the Belgian Highway Department most usually shop welded and field riveted its bridges on the basis of economy determined by experience. However, it was pointed out that this was not a hard and fast rule, some of the bridges being all welded. It was also reported that railway bridges are usually riveted in Belgium.

In the design of welded highway bridges the allowable tensile stress used is 16 kg/mm^2 (about 22,000 psi) for ordinary steel or 22 to 25 kg/mm^2 (about 30 to 35,000 psi) for special low-alloy steels. In either case impact is figured as 1.05 times the total dead load plus live load. This factor was formerly 1.5, but has recently been reduced on the basis of experience and tests. The analysis of the two steels used (identified as A37 and A52) were not obtainable. However, it was stated that open-hearth, fully killed steel was specified for important bridge components. Moreover, such steels were purchased on chemistry and mechanical properties including impact at —20° C (—4° F) and an underbead cracking test. Investigation is now under way by the Belgian Highway Department in the use of composite bridges of steel frames and prestressed concrete acting together. Results are not yet available.

Among other bridges discussed were a shop-welded field-riveted highway arch bridge in Finland, a Vierendel highway truss in Switzerland and a 1200-ton bridge said to be the northernmost welded bridge in Norway. These structures were made of steel produced by a propietary oxygen process.

In Holland, examples of welded highway bridges and repaired railroad bridges were noted. It was stated that these bridges represent the usual practice in that country. Bessemer steel is used for such structures. A typical analysis is 0.15 to 0.20% C and 0.60 to

0.80% Mn. The corresponding mechanical properties are 37 kg/mm² (52,000 psi) tensile strength, 26 kg/mm² (36,000 psi) yield point and 25 to 30% elongation in 2 in.

The steel is usually purchased to mechanical properties alone, but chemistry is reported and considered.

No evidence was seen in Europe of the welding of tier-type buildings. However, it should be remembered that tall, multi-story buildings are the rare exception in Europe. In the fabrication of new mill buildings, power stations and other industrial buildings, there were examples of all-riveted, riveted and welded and all-welded structures. The predominance, including those buildings housing the plants visited, seemed to be of welded fabrication with erection by riveting. Similarly the all-riveted building was the exception.

Among the statically loaded structures which were noted were bents for mill buildings, transmission towers, and structural frames for power stations. A notable example was seen in Holland. A series of rigid frame bents of 50 meter (164 ft) span were being fabricated. These consisted of welded knees, a beam span of three plates and four column supports. These bents were all welded, with submerged-arc welding used for all long seams.

In the same plant twenty all-welded rigid frame bents, 75 tons each, were being fabricated for a power station in the United States. Here again submerged-arc welding was widely used and the structures were to be both shop and field welded.

Roof trusses were most usually welded in whole or in part. Many light trusses were seen in different plants, composed of angles or small I-beam members which were welded directly to the chord members. In one case the angles were flattened at the connection, but this was not usual. In several cases, as in Norway, Germany and Holland, very light roof trusses were riveted. In two cases the explanation offered was that the weight which could be saved in structures of this size by welding could be more than compensated for in the case of riveted fabrication, with less precise fit-up required and elimination of the problem of straightening very light members.

A third type of construction classified here under structural steel, of which a notable example was seen in Germany, is the construction of large cranes and power earth-moving and handling equipment such as shovels, buckets, etc.

Crane runway girders in plants built since World War II are almost 100% welded. The same can be said, possibly to a slightly lesser extent, of the crane spans themselves. In the German plant cranes for shipyards and cargo handling of every size and description are being fabricated from welded plate assemblies. A large 25-ton, 3-legged, Gantry Luffing Crane was being built for use in Egypt. A crane of similar construction was built for a U. S. Navy installation in Florida. It was obvious that emphasis was placed on design in this plant so that maximum use could be made of all steel used and material conserved to the fullest extent. Prototypes are built for each new design and tested using strain gages before the final design is agreed upon and placed in production. Production methods are highly efficient and obviously carefully planned. Some use is made of automatic submerged-arc welding, but for the most part manual welding is used. Assemblies are stress relieved at 550 to 600° C (1050-1100° F).

In general it was obvious that welding practices in this field were up to American standards. Plate edges are prepared most usually by manual oxygen cutting, although machine oxygen cutting is used to some extent. Welds are of good appearance and of proper size and proportion. Details are generally comparable to United States practices, the omission of welding of intermediate stiffeners to tension flanges of girders, for example. Use is made of submerged-arc welding, the extent varying quite widely from one plant to another.

In general the steels used, usually the same for bridges and buildings, are of a lower carbon content than those used in the United States. This fact, together with the practice of using thinner sections, would seem to explain the lack of concern in Europe for what is known in the United States as "weldability." No case was encountered where preheat was used. As in the United States, inspection is almost entirely by visual means.

A distinct preference exists in Europe for the fabrication of members from plates rather than rolled sections. This is possibly due to the relative cost of steel and labor. In Germany, for example, in one plant it was reported as more economical to use up to 80 manhours of labor to save one ton of steel. (The average German ratio quoted was 1 to 50 and a United States ratio quoted as one ton to 20 man-hours.) This difference between European practice and American practice should not be explained away entirely, however, by these ton to man-hour ratios. The structural fabrication seen in Europe suggests that in any case more care is given to design, and economies are thus effected in labor as well as materials.

In so far as production facilities, these varied widely according to the size and newness of the plant. In some plants the production layouts, welding and handling facilities were especially impressive. There were cases of the opposite as well.

Research in structural welding is being carried on in several European areas. The British Welding Research Association is currently conducting fatigue studies in butt-welded joints. The Association de Industries de Belgique is conducting a program of research on the effect of cyclic loading on structural assemblies of different designs. Structural research on welded designs and connections is also being carried on at the College of Manchester, England.

The foregoing is by no means a complete report of any single visit, nor of all visits. The applications cited have been selected as representative of the over-all picture. To us it suggests that welding is becoming the principal means of structural joining in

Europe. The need for replacement of equipment destroyed during World War II has contributed largely to this condition.

PRESSURE VESSELS, TANKS AND PIPING

Welding is being used almost exclusively in the fabrication of pressure vessels, both fired and unfired, and storage tanks including spheres, large liquid containers, both stationary and mobile, pen stocks and cement kilns. Riveting was seen in this field of application on portions of cement kilns being fabricated in Denmark. The extent of welding in this field in Europe is essentially the same as it is in the United States.

The materials used in Europe for pressure vessels, tanks and piping are essentially the same as in the United States. They prefer to use steels with a 0.23% maximum carbon using higher manganese to meet the mechanical properties required. They are using either aluminum or silicon killed basic open-hearth or electric-furnace steel.

It is quite common in Europe for the steel producer to fabricate welded structures of plate produced in his mill. In one steel mill in Germany they are using up to 75% of their own plate output in welded structures. The majority of the steel producers visited fabricate products consisting of pressure vessels, tanks and piping. While not many heavy wall pressure vessels were noted it is our understanding that the mills fabricate most of the pressure vessels used in Germany.

Basic (low hydrogen) type electrodes are used almost entirely in welding pressure vessels, tanks and piping.

The design of pressure vessels, both fired and unfired, is essentially the same as in the United States. One company in France has a new plant where they are building pressure vessels and spheres, primarily for the chemical industry, which are almost exact duplicates of those made by a plant in the United States. In this case, as in many others, these companies are licensed by companies in the United States to fabricate products to the United States design.

In Switzerland one company building penstocks is using reinforcing ribs on branch connections which are not welded to the pipes. The reinforcing rib (three pieces) is fitted very accurately to the pipe and welded into a continuous section. This company maintains that this type of reinforcing rib is more effective and less costly than one which is welded to the pipe.

A company in England is making containers for transportation of liquids. They are building some of the largest gasoline trailers for tractor-drawn vehicles used in Europe. The use of welded construction permits design features which would be impractical by other means of fabrication.

Mechanized submerged-arc welding is used very extensively for longitudinal and circumferential joints in pressure vessels and piping. The most common practice is to use manual shielded-metal-arc welding for the backup pass. For plates up to 1¼ in. thick, single pass submerged arc welding is used. For heavier sections, one pass is made from the inside and one from the outside. In general, plate thicknesses did not exceed 3 in. in the shops visited. A limited amount of mechanized arc welding with continuous coils of covered electrodes is being used in a very few shops. In one case relatively small diameter spheres are being joined entirely by manual welding.

Extensive use is made of machine oxygen cutting of plate to size and for edge preparation using multiple torches. However, edge planers are used more often for the edge preparation of plates, particularly where submerged arc welding is used. Edge preparation and weld appearance are very good and, we believe, equal to what is being done in the United States. Most of the plates are formed into cylinders by rolling. In a few instances, in older plants, heavy presses are being used to progressively form plates into half cylinders.

Quality control in the fabrication of pressure vessels, tanks and piping appears to be excellent with great care taken to control all variables during manufacture. In general, more use is made of nondestructive testing than would be required by United States codes for similar vessels. Radiography is the most commonly used nondestructive test, as is the case in the United States. In a number of cases magnetic particle inspection as well as sonic tests are being used. Techniques for supersonic testing welded joints are being developed as is a means for locating the depth of defects below the surface. They have not as yet developed standards for interpretation of supersonic tests of welded joints. At present they are using sonic tests as a supplement to the X-ray test for quality control purposes.

In general, the work and welding head positioners for mechanized welding being used are very good. In this respect, their equipment and facilities are very similar to those used in the same industries in the United States. The extent to which they use handling facilities appears to be purely a question of economics.

LIGHT ALLOYS

A limited number of the plants visited in Europe are engaged in the welding of light alloys. Except from an experimental standpoint, no welding of magnesium-base alloys was seen. In the welding of aluminum, inert-gas metal-arc welding, using a tungsten electrode is generally used. One application in England uses the consumable electrode method for welding aluminum. Argon is used exclusively; helium is not available in Europe. In two plants, use is made of flash welding in the fabrication of aluminum window frames. In other applications, spot or seam welding is used. From the information that was obtained, the aluminum alloy used in Europe generally contains 3 to 4% magnesium. In some of the nonconsumable method applications, the aluminum filler metal is a 5% silicon alloy.

A French plant is making welded aluminum auto-

mobile bodies. The bodies and some parts of the automobile are produced using inert-gas metal-arc welding, nonconsumable electrode method and spot welding with portable guns. In England, aluminum structures with a thickness of approximately 3/8 in. are welded using the consumable electrode method. In Norway, aluminum life boats, life rafts, ladders and transport packs are welded using the nonconsumable electrode method. In Denmark, the same method was seen used in an experimental setup. In Belgium, rather extensive use is made of the nonconsumable electrode method for welding bulkheads and roof sections of railroad cars. Spot welding is also used in this application. In Switzerland, sheet aluminum is used in combination with extruded shapes, using the nonconsumable electrode method of inert-gas metal-arc welding.

Use of light alloys in Europe, as far as this Mission observed, is somewhat less than that in the United States. Almost all the welding of aluminum alloys is carried out using the nonconsumable electrode method. No heavy aluminum sections were seen. The use of the consumable electrode method was observed for only one application. It is felt that the companies which were visited on this tour might not be entirely representative of the amount of welding of aluminum which is carried out in Europe.

CONCLUSIONS

The foregoing report necessarily reflects only what we observed and only the information available to us in the plants visited during the tour. While variations from the practices cited could surely be found in other European companies, we feel that they are representative of over-all European welding practices.

The American members of Mission 250 have been keenly interested in obtaining technical details in so far as possible. At the same time we have tried to form basic impressions from what we have seen which would make possible a comparison of European and American welding practices. These may be briefly summarized as follows.

We believe that European industry is technically advanced to the same extent as American industry. This is a fact which may not be sufficiently appreciated in the United States. Moreover, from the standpoint of productivity it is clear that more man power and less mechanization is used in Europe than in corresponding operations in the United States. We believe this difference is based on economic considerations and the relative costs of labor and materials rather than a lack of familiarity with mechanization methods. European industry is surprisingly well aware of overseas developments in this as in other industrial aspects. We are convinced that if economic considerations or conditions in the world market would require it, European industry could readily increase its productivity accordingly.

It remains for American industry to decide whether contact with European activities is advantageous for a continuing exchange of ideas and developments and, if so, the nature and extent of participation in organizations such as the International Institute of Welding and the International Standards Organization.

The first American warship constructed of iron to use steam was the MICHIGAN built in 1842.

W. LEE WILLIAMS and JOHN F. ECKEL

*STRESS CORROSION OF AUSTENITIC STAINLESS STEELS IN HIGH TEMPERATURE WATERS**

THE AUTHORS

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Previous articles authored or co-authored by Mr. Williams have appeared in the November 1948, August 1949 and November 1950 issues of the Journal.

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STRESS CORROSION may be defined as that type of corrosive attack that results from the combined action of stress and a corrosive environment. Stress corrosion has been observed in most of the common metallic materials. The attack results in the formation of cracks that continue to grow until failure occurs or until the nature of the stress system and/or the corrosive environment change sufficiently for attack to cease. The rate of crack propagation may vary considerably depending upon environmental conditions. Cracking may occur as intergranular cracks, transgranular cracks or a combination of both. Generally, cracking of austenitic stainless steels will be transgranular in nature unless conditions exist within the material that encourage intergranular corrosion. In such cases, intergranular cracking may be prevalent.

Stress corrosion has been found in most of the common metallic systems and reported in the literature.[1,2,3,4,5] The specific corrosive environments in which the more common alloys have been known to crack have been reviewed by Copson.[6] Most of the corrosive media reported are exceedingly mild and have been found to produce little or no attack in the absence of stress.[5] Stresses necessary to cause stress corrosion must be tensile in nature on surfaces exposed to the corrosive medium. They may be localized within single grains, groups of grains, or they may be general over the entire surface. Such stresses may be residual, applied or a combination of both. Residual stresses assume a greater importance in practice than do applied stresses. This is true because residual stresses cannot be properly evaluated and vary considerably in magnitude, whereas applied stresses are generally determined by the design engineer and proper allowances made. In many cases where stress corrosion has been a

*This paper is a much condensed version of selected information from a chapter on stress corrosion to be included in a Wear and Corrosion Handbook for Water Cooled Reactors. The Handbook is being prepared on Navy Contract by the Westinghouse Electric Corporation, Atomic Power Division. The Handbook is scheduled for publication in the spring of 1956.

troublesome problem, stress relief annealing has been helpful. In other instances, care in fabrication with close control of mechanical and thermal treatment has materially reduced the problem.

Besides stress and corrosive media, several other factors add to the complex nature of stress corrosion. Such factors as time of exposure, temperature of exposure and the internal structure of alloys have been investigated and much learned that has aided in the establishment of practices to reduce the number of failures. Two other factors that may have an important bearing on the problem, when more fully understood, are plastic strain, and the behavior of protective films in mildly corrosive media.

This paper deals with some of the aspects of stress corrosion of austenitic stainless steels when exposed to high temperature water and steam. The literature applicable to this type of exposure is reviewed and new data are presented showing the effect of some factors on the susceptibility of stainless steels to such an environment.

REVIEW OF LITERATURE

Stress corrosion of austenitic stainless steels is relatively new, probably because early failures of this type were not recognized as such. Failures of austenitic stainless steels from stress corrosion seem to have been first recognized in the petroleum industry. Dixon[7] described failures in refinery components which were attributed to stress corrosion. Since that time many investigations have shed much light on the phenomenon. However, it is still not fully understood, particularly the mechanism through which cracking starts and is continuously propagated.

Most investigators are agreed that austenitic stainless steels are more susceptible to stress corrosion when exposed to corrosive media containing halides. Since chlorides are the most abundant and most widely distributed of all halides in nature, the chloride ion is considered to be the principal offender. Accelerated laboratory tests used to study stress corrosion usually employ concentrated solutions of the chloride ion as the corrosive medium. A solution of 42 percent $MgCl_2$ boiling at atmospheric pressure is one of the most widely used.[8,9,10] Solutions of concentrated calcium chloride have also been used,[11] and Edeleanu[10] has reported results using other chloride salts. Another corrosive medium recently developed and now currently employed in studying stress corrosion cracking of stainless steel employs a solution of sodium chloride with an oxidizing salt added.[12]

Useful information for the designing engineer would concern the effect of time of exposure to the corroding media. Reliable information of this type has never been accumulated. That it might be accumulated seems unlikely because all of the contributing variables are interrelated. Thus, small variations in the stress level, changes in the corrosive media, temperature fluctuations, etc. may be expected to influence the length of time required for stress corrosion to start as well as the rate of crack propagation. Such variations must be expected under service conditions, but even with carefully controlled laboratory experiments, considerable variation in time to failure has been observed. Thus, it seems best to consider the time variable as a dependent variable. Nathorst[11] best illustrates how the time factor may vary in practice by a discussion of the service life of 25 steam heated boilers. These boilers were fabricated by the same manufacturer and were presumably identical components. The distribution of service life is tabulated below.

Number of Boilers	Approximate Service Life, Years
3	1
4	2
10	3
2	4
2	5
3	7
1	9

It seems reasonable to believe that a limiting stress should exist below which no stress corrosion should occur. However, efforts to establish such a threshold value have not been entirely successful. One of the first values reported placed the limiting stress at about 10,000 psi,[8] and this has been quoted repeatedly in the literature. However, there is no general agreement as to the value of a threshold stress. The non-uniformity of stressing from one grain to the next as pointed out by Krivobok[13] may well explain this lack of agreement.

It is common knowledge that stressing to the yield strength renders stainless steel much more susceptible to stress corrosion. This fact suggests that plastic deformation may be an important factor, and there is ample supporting evidence.

It is a well known fact that plastic deformation will promote some sluggish solid state reactions. For instance, the usefulness of Hadfield's manganese steel stems from martensitic formation resulting from plastic deformation at ambient temperatures. It has been shown by Fiedler, et al[14] that the martensitic transformation is also enhanced in austenitic stainless steel by small amounts of plastic strain. In his investigation of stress corrosion, Edeleanu[10] observed that cracks closely followed plates of quasi-martensite in a steel containing 8%Mn, 4%Cr and 8%Ni. This led him to suggest that the attack was preferentially localized on the quasi-martensite. He demonstrated susceptibility could be decreased either by stabilizing the austenite so that no quasi-martensite existed or by adjusting the composition to produce large amounts of martensite. Waber[15] observed polished surfaces were more susceptible to stress corrosion than pickled surfaces. He loaded annealed samples of A.I.S.I. 302 to 90% of the yield strength (0.01% offset) and exposed them to boiling 42% $MgCl_2$. Cracking occurred in polished areas but not in pickled areas. Franks, et al[9] observed that cold working severely by deep drawing renders stainless steel more susceptible to cracking in 42% $MgCl_2$ than cold working by simple bending or by

rolling. Davis[16] reported that failures in stainless steel bellows were related to the direction of rolling. He confirmed his observations by testing two horseshoe samples in a sodium chloride solution containing 18 ppm chloride. One sample bent parallel to the direction of rolling failed by cracking in 4 hours. Another sample bent normal to the direction of rolling did not crack after 50 days of exposure and showed only slight pitting.

THEORIES OF STRESS CORROSION

Harwood[17] has recently reviewed various theories proposed to explain stress corrosion. Although no single theory has been proposed that adequately explains all of the known facts, the electrochemical theory is the most plausible. Mears and Brown[18] found marked differences in potential between grain boundaries and grain centers and also between two different phases within an alloy. The fact that application of cathodic currents can inhibit attack must be considered as substantial evidence that stress corrosion is electrochemical in nature.[18,19,20]

It is generally believed that stress corrosion starts as a highly localized attack. Logan[21] observed that when stainless steel was abraded in argon, its surfaces were more electro-negative to a calomel electrode than when abraded in normal atmospheres. From this fact he reasoned that stress corrosion could start at film free areas since they were anodic to the filmed areas. Such film free areas would be expected on stainless steel only where film defects occurred or where the film had been ruptured, and an active surface existed.

Some recent work on stainless steels is of particular interest in connection with the probable mechanism of stress corrosion. Hoar and Hines[22] measured the potential of small wires during exposure to boiling 42% $MgCl_2$. The forms of their time-potential curves are indicated in Figure 1. The drop in potential immediately after exposure was explained by the existence of corrosion currents between the "pores" in the oxide film (anodic) and the polarized film itself (cathodic). The increase in potential was attributed to film repair resulting from the precipitation of hydroxide. During the increase in potential, the hydrogen-ion concentration within the "pores" was presumed to increase. The second drop in potential thus

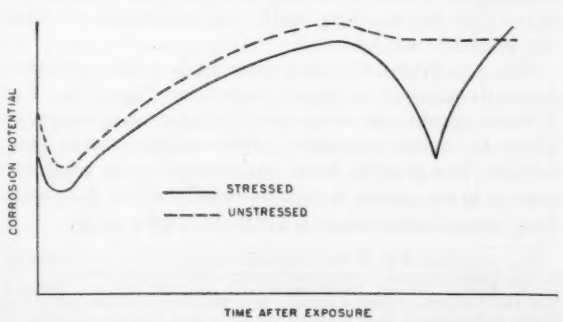

Figure 1. Corrosion potential of austenitic stainless steel wire as a function of time in boiling 42% $MgCl_2$. (After Hoar and Hines.)

was believed to occur when the acidity within the pores became high enough to dissolve the hydroxide and to form soluble metal products. At this point, pitting was presumed to begin. Stressed specimens followed the same general pattern as unstressed specimens with three important exceptions. The general level of potential was lower, the second drop in potential was much greater, and it was followed by a marked increase in potential. No extension of the stressed specimens was observed until second drop in potential began. Extension then continued until failure from stress corrosion occured at the minimum potential reached. The second rise in potential was attributed to film repair on the unstressed fractured ends of the wires. From these results, it was concluded that the major portion of the life of the wires consisted of the period of film breakdown.

INDUSTRIAL EXPERIENCE

Early failures in stainless steel attributed to stress corrosion[7] included such petroleum refinery equipment as heat exchanger tubes, condenser tubes and pressure vessel linings. Since that time, the list has grown and now includes items ranging from coffee urns to heavy industrial equipment. In most cases, chlorides have been considered the principal offender. Other corrosive media have also been considered responsible for certain failures. Nathorst[11] has described a number of industrial failures involving many corrosive media. Many of these contained chlorides.

A number of failures in austenitic stainless steels have been attributed to stress corrosion in equipment with high temperature water or steam as the corrosive medium. Some of these have been selected for review for two reasons. First, the corrosive media are similar to those employed in tests described below and second, they illustrate the effect of concentration, another variable that often exists in service but is not commonly studied in laboratory investigations.

Davis[23] described the failure of a stainless steel (Type 304) turbocompressor through stress corrosion of two rotors. Failure by transgranular cracking occurred after three months of service. The unit was used to compress steam which was subsequently condensed. The condensate contained less than 0.5 ppm total solids. However, chlorides were present in the raw water to the extent of about 20 ppm and were also found in a non-metallic deposit on the failed parts. Failure was attributed to concentration of chlorides, which were presumed to have entered the compressor through the medium of finely divided particles of water.

Another case described by Davis[24] occured in the tubes of a heat exchanger. Normal temperature on the process side was 350°F to 380°F, and in emergencies this could reach 500°F. The outside surfaces of the tubes were exposed to cooling water with a chloride content of 110 to 420 ppm. Examination showed that the tubes were cracked from the water side. The cracks had originated under a non-metallic deposit on the under side of the tubes. This deposit may have permitted concentration of chlorides on the metal surface and at the same time caused a rise in

temperature. The stresses were believed to have been residual to the forming operation. This conclusion was reached when the cracks, which in the original specimen were just barely visible, opened 1/32 inch when the pipe was sectioned.

Davis [24] also noted another failure in which conditions favorable to concentration existed. This occurred in a vapor heated steam generator after only 90 hours of service. It was believed that a small vapor space existed in the shell directly under the upper tube sheet. A heavy deposit of a non-metallic substance was found in this area, and transgranular cracks originated on the water side. Water analysis showed only 13.5 ppm chlorides.

Additional failures have occurred in vertical tubular heat exchangers where the cooling water was low in chlorides, but the existence of a vapor space under the upper tube sheet was probable. Even though boiling on tube surfaces may not have occurred, it is probable that fluctuations in water level and turbulence afforded opportunity for the concentration of chlorides.

Collins[25] has described failures in vertical condensers where vapor spaces actually existed under the upper tube sheet. This resulted in concentration under non-metallic deposits. He also pointed out two design changes and one operational change that corrected the condition. Each of these was in the direction that reduced the tendency for concentration.

Three small waste heat boilers described by Collins[25] are of particular interest because they provided another means of concentration. These boilers were constructed of Type 316 stainless steel, all of the same basic design. Two of these boilers failed from stress corrosion originating in a crevice between a backing strip and the weld joining the top tube sheet to the top flange. The other boiler failed from stress corrosion originating in crevices between the tubes and the lower tube sheet. The condition was materially improved in a rebuilt boiler by the elimination of crevices where concentration could occur.

A detailed review of the above industrial experience leads to the following conclusions.

1. Chlorides were present in all instances and have been considered the cause of stress corrosion. In each case, a condition existed that favored concentration in the region where failure by cracking occurred. Therefore, the existence of conditions favoring concentration may be a more important consideration than the actual overall composition of the water.

2. In many cases, changes in design, construction or operational procedures which eliminated or minimized concentration were successful mitigation measures.

3. No information on the amount of oxygen present was available. In view of experimental results discussed below, the effect of oxygen concentration cannot be neglected.

4. All cracking was transgranular in nature.

LABORATORY INVESTIGATION *

Available information, as described above, clearly indicated that stress corrosion was a significant problem in the design and operation of stainless steel equipment to be used in contact with high temperature water. Unfortunately, the information did not define clearly the conditions under which stress corrosion cracking would or would not occur. The remainder of this article describes briefly a laboratory investigation conducted to throw additional light on this subject.

The laboratory test program was quite extensive. It involved the study of numerous variables, some in considerable detail. However, this account of the test program is not burdened with a mass of data. Instead, the story is told in narrative form, with a brief description of procedure, conclusions reached, and illustrative data only as needed for clarity.

The subject matter is arranged in two main sections: (1) tests of small laboratory specimens to determine effects of variations in material and environment, and (2) tests of small boilers to confirm results under more realistic conditions.

SECTION I—SPECIMEN TESTS

Procedure

Stress corrosion tests of small laboratory specimens were conducted in electrically heated stainless steel pressure vessels. Two basic vessel types were used. One was a hydraulic loop, which was a semiclosed system through which high temperature water could be circulated past the specimens. Circulation was accomplished with a stainless steel "canned rotor" pump.

The second basic type of vessel was an autoclave. Such a vessel could be used either for static exposure, or for dynamic exposure by utilizing some form of external drive. The liquid level was maintained at $\frac{1}{2}$ to $\frac{2}{3}$ full, and specimens could be exposed in either the steam phase or the water phase.

Waters of known composition, including gas content, were used as corrosive media. The water composition usually changed somewhat during the course of an experiment. Such changes were greater in the autoclave tests where the water was of relatively small volume and not replenished continuously. Composition changes were noted especially in regard to oxygen content, as the oxygen was sometimes scavenged by reacting with the specimens or with the pressure vessel itself.

The majority of the tests were made with specimens basically similar to those shown in Figure 2. The U-bend specimens were used to determine suspectibility to stress corrosion under severe stress conditions. The simple beam specimens were used for tests at lower stress levels, especially when the stress level was of interest as a variable under study.

*The work described in the remainder of this paper was performed at the Knolls Atomic Power Laboratory, a laboratory owned by the U. S. Atomic Energy Commission and operated by the General Electric Company under Contract No. W-31-109-ENG-52; at Bettis Plant, a laboratory owned by the U. S. Atomic Energy Commission and operated by the Westinghouse Electric Corporation under Contract No. AT-11-1-GEN-14; and at the U. S. Naval Engineering Experiment Station, Annapolis, Maryland. The work was performed at the request of the Government in connection with its SIR and STR projects.

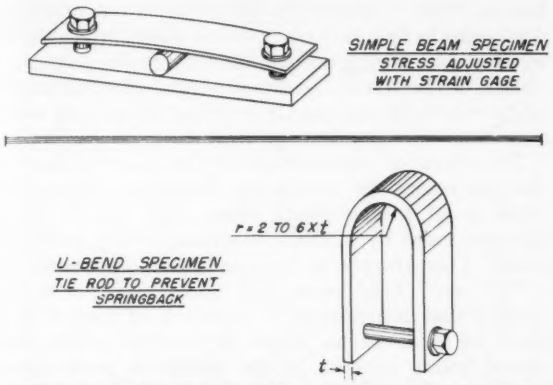

Figure 2. Basic stress corrosion specimens used in the majority of the laboratory tests.

The specimens were exposed in the pressure vessels for various times. Two weeks were usually sufficient to produce failure where failure was likely to occur. However, environments which were not conducive to failure were sometimes checked out for several months to make sure that a time variable was not a significant cause of negative results.

Failed specimens were those in which stress corrosion cracks were observed. Such cracks always developed in areas under tensile stresses. The cracks were usually visible at no or low magnification, and sometimes progressed to complete specimen fracture. In questionable cases, the presence of cracks was determined by microscopic and metallographic examination.

Results in High Purity Water

High purity water is defined, in this case, as water having a total solids content of less than 1 ppm and a resistivity of at least 500,000 ohm-cm. Such water was prepared by distillation and deionization. A gas (usually oxygen) was added in most tests.

The stress corrosion behavior of austenitic stainless steels in high purity water was not explored as extensively as might be desired. However, sufficient tests were conducted to conclude that stress corrosion cracking would occur rarely, if ever, in structural components fabricated of hot rolled-mill annealed material. Subsequent introduction of stresses, from fabrication and service, should not lead to difficulty even if the stresses somewhat exceed the yield strength of the material.

On the other hand, heavy cold working was shown to cause susceptibility to stress corrosion in high purity water, especially if the water contained appreciable oxygen.[26] This indicated that austenitic stainless steels should not be used in the cold rolled or spring tempered conditions. Subsequent annealing was found to be an unreliable method to remove the harmful effects of prior heavy cold working.

There remains a possibility that an occasional stress corrosion failure might occur in equipment fabricated from mill annealed material, but excessively cold deformed during fabrication. At least one interesting case was observed. Leaks developed in two sections of ¼" Type 347 steel tubing installed at orifice meters in a hydraulic loop apparatus being used in the conduct of corrosion tests. The tubing apparently was obtained in the mill annealed condition, but was worked by severe cold bending during fabrication of the loop. Installation was in an area likely to have caused exposure to water vapor as well as to the water itself.

Failure developed after the loop had been operated 1550 hours at 600°F and 4200 hours at 500°F. At various times the water in the system had been degassed or had contained 1 to 5 ml/l of oxygen or 20 to 30 ml/l of oxygen. A typical cross section of the failed tubing is shown in Figure 3. Similar tubes in other loops did not fail, and the exact reason for this particular casualty is not certain.

Results in Boiler Water

Insofar as stress corrosion is concerned, the most important single characteristic of naval boiler water is the probable presence of chlorides. The preponderance of published information points to chlorides as the main culprit causing stress corrosion failures of austenitic stainless steel. Also, it is now known that oxygen plays an important role in the stress corrosion process.

There is no reason to believe that the actual mechanism of the stress corrosion process in the water phase is any different from that in the steam phase. Nevertheless, it is necessary to make a distinction between the two phases in determining whether stress corrosion will or will not occur within a particular steam-water system.

There are several reasons for this. First, corrosion inhibitors may be effective in one phase and not in the other. Second, oxygen may be present in unequal distribution between the phases. And last, but perhaps most important, the dissolved solids in the water can become concentrated on parts exposed in the steam. This can come about from splashing, water carry-over, rising and falling of water level, start and

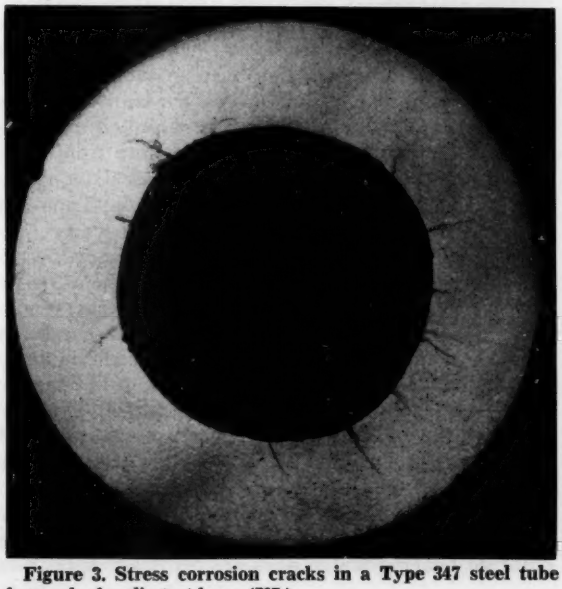

Figure 3. Stress corrosion cracks in a Type 347 steel tube from a hydraulic test loop. (X7.)

shut-down operation, penetration of water through deposits and evaporation from hot surfaces, and periodic flashing to steam of water which enters crevice areas of heat transfer equipment. Joint crevices between tubes and headers are especially vulnerable locations, as welding and/or tube rolling introduces stresses in adjacent areas.

For the above reasons, it is convenient to separate the water and steam phase tests in the presentation of the boiler water experiments.

Water Phase Tests. Very few tests were made in plain chloride bearing water, for two reasons: (1) boiler systems in service would mostly use alkaline-phosphate treated water, and (2) water phase problems did not prove to be as serious as steam phase problems.

The few tests made did demonstrate that stress corrosion cracking could occur in plain chloride bearing water, at least if some oxygen was present. Cracking was observed at temperatures nearly as low as the atmospheric boiling point and at chloride levels as low as 300 ppm. The region below 300 ppm chloride was not explored sufficiently to determine if some threshold chloride level existed (other than zero) below which stress corrosion would not occur.

In contrast to the limited data on untreated waters, a great number of tests were conducted with stainless steel specimens submerged in alkaline-phosphate treated waters.[27] These tests explored such variables as chloride level (1 to 20,000 ppm), oxygen content (0.005 to 200 ppm), temperature (467° to 500° F), time (7 to 140 days), pH (10.6 to 11.3), and material (annealed Types 304 and 347).

Of nearly 500 specimens exposed within these limits, only three cases of stress corrosion were observed. The three failures could be explained as having been caused by inadvertent exposure to the vapor phase during a part of the test period. Thus, the evidence was overwhelmingly in support of the conclusion that alkaline-phosphate water treatment could inhibit the stress corrosion of austenitic stainless steels submerged in any boiler water likely to be encountered under practical circumstances. The inhibiting action would include waters known to have sufficient chloride and oxygen to produce cracking in the absence of the alkaline-phosphate treatment.

The above conclusion was not found to apply to sensitized stainless steel.[28] For example, Type 304 steel failed in alkaline-phosphate treated water (except possibly when the chloride was kept very low) if the steel was previously sensitized intergranularly by heating to 1200°F. The stress corrosion cracks progressed intergranularly. (Usually stress corrosion cracks in austenitic steels follow a predominantly transgranular path.) The tests pointed to the danger of using a steel which is subject to sensitization either from welding or operating temperatures. A stabilized grade, such as Type 347 steel, would be preferred for this very reason.

Steam Phase Tests. Exposure of austenitic stainless steels in the steam phase of high temperature chloride bearing water does not, in itself, appear to lead to stress corrosion cracking. However, cracking does seem to be a serious problem when intermittent wetting and drying occurs, thereby causing concentration of the water constituents. The circumstances under which this can occur in actual equipment were mentioned in a previous paragraph.

The effects of intermittent wetting were studied in the laboratory by mounting specimens above the water level, in the steam phase, and then wetting the specimens by periodic inversion of the pressure vessel. This procedure became popularly known as a "tilt test." Trial runs with porous specimens indicated that concentration factors of at least 4 to 8 could be obtained, as judged by analysis of the dissolved solids content in the specimen pores after exposure. A slight amount of superheat (perhaps 5°F on the average) provided the necessary heat gradient to cause evaporation of the water from the specimens. Various vessel tilting cycles were employed, but the most common one consisted of inverting the vessel for a few seconds twice a day.

An important finding from such tests was that alkaline-phosphate water treatment would not inhibit stress corrosion in the steam phase. But of perhaps greater importance was the discovery of an apparent relationship between oxygen and chloride contents that seemed to control the development of cracks.

This relationship is shown graphically in Figure 4. The graph was prepared by plotting available data from tilt tests[27] in which oxygen and chloride contents were considered as primary variables, and in which all other variables were considered as secondary and not included in the analysis. The actual range of conditions covered in the tests was as follows:

Constants:	
Condition of steel	Annealed
Stress (U-bend specimens)	Beyond yield
Tilting frequency	Twice daily
phosphate	50 ppm
pH	10.6
Primary variables:	
Chloride	0.1 to 553 ppm
Oxygen	0.04 to 200 ppm
Secondary variables:	
Steel, AISI types	304, 305, 316, 347
Temperature	467° to 500° F
Testing Time	1 to 30 days

Figure 4 represents, in a rough way, the relationship believed to exist between the chloride and oxygen contents and stress corrosion cracking in the steam phase, with intermittent wetting and the associated concentration of water constituents. It appears that both oxygen and chloride must be present to some extent if stress corrosion is to occur. The dividing line between safe and unsafe water compositions has certainly not been well defined. Indeed, it is doubtful that a definite division could be established without precise definition of alloy, treatment, time, temperature, stress, frequency of intermittent wetting, and perhaps other factors. However, it does appear that the maintenance of oxygen at some value below 1 ppm (perhaps 0.5 ppm in critical areas) will provide reasonable assurance against stress corrosion

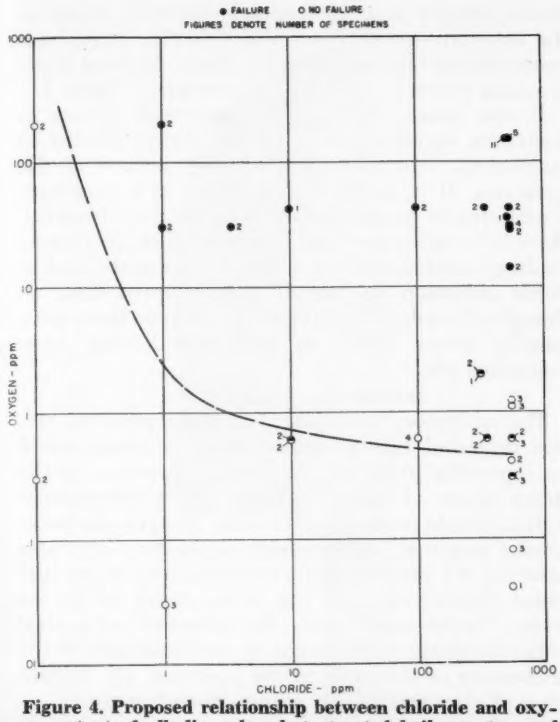

Figure 4. Proposed relationship between chloride and oxygen content of alkaline-phosphate treated boiler water, and susceptibility to stress corrosion of austenitic stainless steels exposed to the steam phase with intermittent wetting.

failures at chloride levels likely to be encountered in steam generation equipment.

The test program included numerous other experiments in which different variables were explored in more or less detail. There is no need to complicate this article with detailed descriptions of all of these experiments. However, some are of sufficient general interest to warrant limited description.

For the most part, these miscellaneous tests were conducted under the following conditions:

Exposure: steam phase, wetted by vessel inversion twice daily.
Test time: 15 days, average.
Water: Cl–530 ppm, PO_4–50 ppm, pH–10.6, and aerated (no attempt made to remove gases before sealing autoclave).
Temperature: 500° F.
Material: Types 304 and 347 austenitic stainless steel, annealed before stressing.

One experiment was conducted under the above conditions with U-bend specimens ranging in thickness from 0.062″ to 0.41″. No difference in sensitivity to stress corrosion was observed as the thickness varied.

Another experiment was conducted to determine the speed with which stress corrosion cracking could occur.[28] The intermittent wetting frequency was speeded up by tilting the pressure vessel five times, once every four minutes. The total test time was 20 minutes plus heating and cooling time. Cracks were produced within this interval.

A third experiment demonstrated that stresses as low as 5000 psi could produce failure within a 15 day period. Still other tests showed that residual stresses from tube rolling, from tube joint welding, and even from abrading the surface with emory paper were sufficient to cause failure.

Numerous test runs were made in an attempt to find a suitable inhibitor for preventing stress corrosion of austenitic stainless steels in the steam phase of chloride bearing water. The standard alkaline-phosphate water treatment was not effective, as previously mentioned. Tannin, chromate and octadecylamine (a film forming amine) were also tried without success.

Other inhibitor experiments were made with oxygen scavengers added to the autoclaves, as it appeared that stress corrosion would not occur in the absence of this gas. Both hydrazine and sodium sulfite were tried. The results were not too consistent, but they did appear promising, especially in the case of sodium sulfite additions. Stress corrosion cracks occurred only in a minority of cases with sulfite, under conditions which otherwise would have caused guaranteed 100% severe cracking.

The reason for the inconsistent results with sulfite additions is not understood, but it probably is related to a delay in complete scavenging of oxygen in the steam when the sulfite is added to the water. Attempts to hasten the reaction with copper and cobalt catalysts were not successful in eliminating inconsistent results in the autoclave tests.

General Observations. Stress corrosion cracks in annealed austenitic stainless steels are predominantly transgranular. The cracks may vary in appearance from single relatively straight cracks to highly branched finger-like crack networks. Typical examples are illustrated in Figures 5 and 6. It is possible that the straight single cracks are those which are produced under conditions causing rapid crack development, whereas the branched cracks are produced under milder circumstances.

The transgranular crack network is easy to recog-

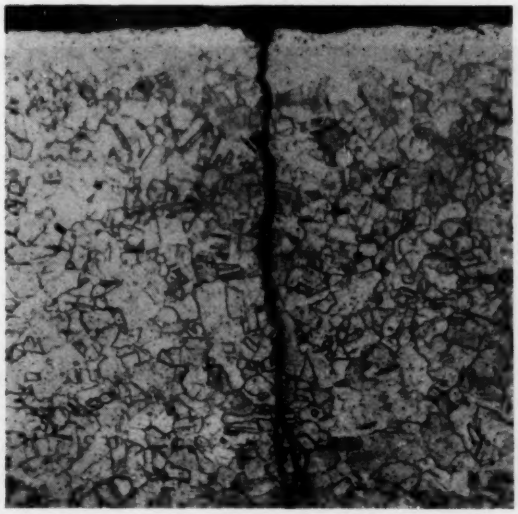

Figure 5. Example of a single, relatively straight transgranuar stress corrosion crack in an austenitic stainless steel. (X250.)

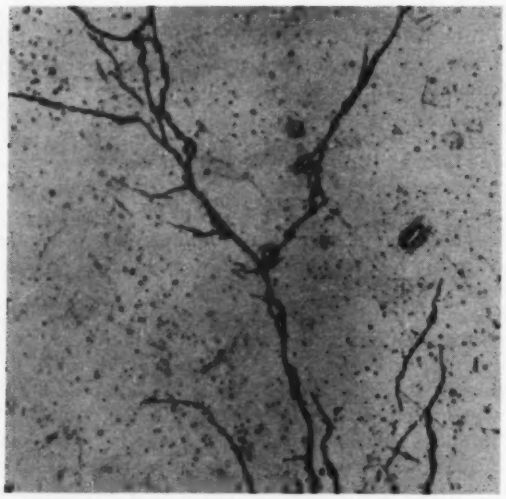

Figure 6. Example of a highly branched network of transgranular stress corrosion cracks in an austenitic stainless steel. (X500.)

nize in austenitic stainless steels as having been caused by stress corrosion. The straight single cracks are less easy to diagnose, because they appear much like fatigue cracks. The diagnosis of the cause of such a crack requires knowledge of the type of stress and corrosive environment leading to failure. The acceleration of stress corrosion by cyclic fatigue stresses is also a distinct possibility. In fact, corrosion-fatigue can be considered as a special case of stress corrosion, the main difference being that stresses are cyclic in the one case and static in the other.

Stress corrosion in sensitized stainless steels may follow an intergranular path. Intergranular attack would usually be found locally in heat affected zones near welds, although it could occur generally in stainless equipment operated at sensitizing temperatures. Differentiation between ordinary intergranular corrosion and intergranular stress corrosion probably would require a supplementary corrosion study in the environment to determine whether stress was necessary for failure to develop. An example of intergranular stress corrosion is illustrated in Figure 7.

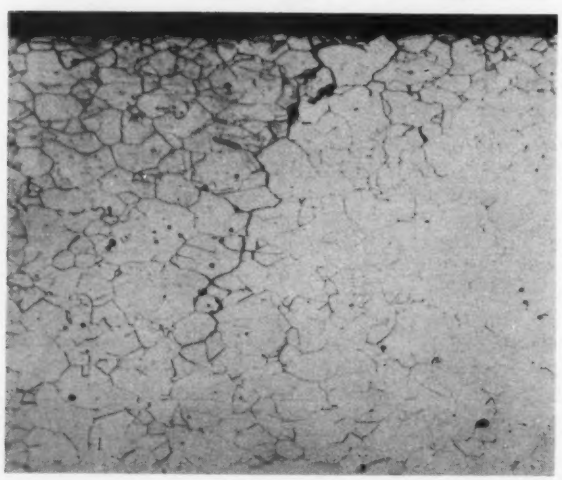

Figure 7. Example of intergranular stress corrosion cracks in a sensitized type 304 austenitic stainless steel. (X100.) (Courtesy, Westinghouse Atomic Power Division.)

It was observed that stress corrosion cracks in austenitic stainless steels nearly always started at macroscopic corrosion pits on the surface of the specimen. It is possible that pitting is a necessary initial step in the development of cracks. However, there is no evidence to indicate that all environments leading to corrosion pits will also ultimately lead to stress corrosion. In fact, it was observed that, although all cracks may have started at pits, there were usually fewer cracks in specimens having more numerous pits.

SECTION II—BOILER TESTS

The laboratory tests described in the previous section indicated that austenitic stainless steels would be especially vulnerable to stress corrosion in the steam phase of boiler systems where intermittent wetting might occur. Of particular concern was tube-header joints of heat transfer equipment, as water entering the joint crevices could flash to steam and cause concentration of the solids dissolved in the water. The laboratory tests also indicated that control of the stress corrosion might be accomplished by (1) prevention of steaming in the crevices, (2) elimination of chlorides, or (3) elimination of oxygen.

Verification of these points under practical circumstances was provided by service and laboratory runs of some small stainless steel boilers. These units were firetube boilers intended for auxiliary services aboard nonmagnetic minesweepers. The boilers were made of welded Type 304 steel. Normal operation was at 260°F and 35 psi. The combustion gas temperature in the "hot end" header was between 1700°F and 1800°F. The maximum metal temperature of the header in the "hot end" was 440°F as determined by measurement.

Critical crevice areas were located in three places. These were: (1) the joints between the tubes and headers, (2) the joint between the combustion tube and one of the headers, which joint was welded with a backing ring on the waterside, and (3) the joints between the headers and shell. A typical longitudinal section through a tube-header joint is shown in Figure 8.

One of these boilers was steamed on a test stand with alkaline-phosphate treated water and no special deaeration. The unit was steamed 1008 hours with water containing 530 ppm chloride, and then an additional 295 hours with water containing 1775 ppm chloride. Tube-header joints were removed for examination after the initial 1008 hours. In addition, samples of the tube-header joints, the combustion tube-header joint, and the header-shell joints were obtained after the full run of 1303 hours. Stress corrosion cracks were found in all cases.

Typical examples of tube-header joint cracks are shown in Figures 8 and 9. All in all, there were 48 tube-header joint sections examined. Of these, 26 had tube wall cracks, 14 had header cracks, and 5 had weld cracks. Some of the tube cracks penetrated the

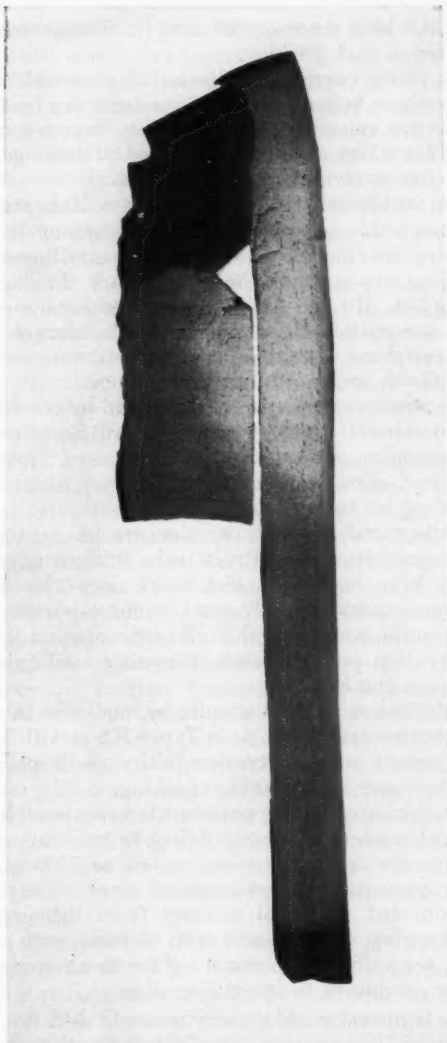

Figure 8. Stress corrosion cracks in a tube-header joint from a Type 304 steel auxiliary boiler (longitudinal section). (X5.)

entire wall, although no malfunctioning from leaks had been observed during operation of the boiler.

Metallographic inspection revealed that the cracks were predominantly transgranular. All occurred within $\frac{1}{4}$" of welds. All cracks originated from the waterside in crevice areas. No cracks were observed at joints which had no crevices.

These observations led to the sampling of tube joints from four similar boilers which had been steamed aboard ship for about 1000 hours. All these joints suffered stress corrosion damage. Stress corrosion cracks were also found in the tube joints of a Type 304 steel hot water heater which had been removed from shipboard service because of leaks after 2000 hours of operation. The hot water heater was a firetube unit operated at a water discharge temperature of 190°F.

A second Type 304 steel auxiliary boiler was operated on a test stand to determine the effects of modified tube joint designs. The boiler was steamed for a total of 1574 hours with alkaline-phosphate treated water, 2.5 to 3.5 epm alkalinity, and no special deaeration. The chloride level was 530 ppm during the first 1048 hours, and 1775 ppm during the final 526 hours. Table I describes the various tube joints and the operating times at which inspections were made.

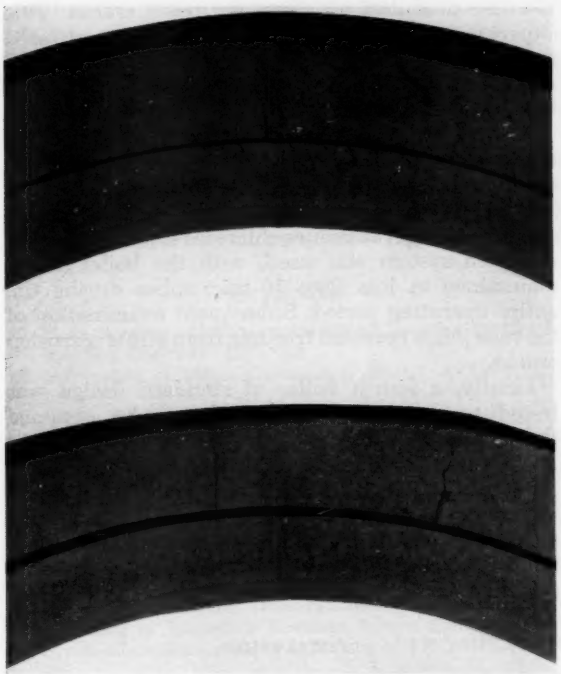

Figure 9. Stress corrosion cracks originating from the crevice of a tube-header joint from a Type 304 steel auxiliary boiler (transverse section). (X10.)

TABLE I
Description of Special Tube Joints
Tested in Type 304 Steel Auxiliary Firetube Boiler

Joint Design No.	Description of Joint	Operating Time When Examined Hours
1.	Standard boiler design. Header beveled 45° to half thickness, welded from fireside.	1048
2.	"J" welded from fireside to near full depth of header.	1048
3.	Same as 2, except Type 316 tubes.	1048
4.	Tube rolled to contact, "J" welded from fireside to half depth of header, then rerolled lightly.	1048
5.	Tube rolled 3 mils on radius beyond contact, then "J" welded from fireside to half depth of header.	1048
6.	Fillet welded on waterside, and small "J" weld on fireside.	1048 and 1574
7.	Same as 1, except tube was plugged to prevent gas circulation, and ends were water cooled to prevent steaming of boiler water in joint crevice.	1574

Joint designs No. 1 through No. 5 all led to severe stress corrosion cracking. From this, it was concluded that deep "J" welds and tube rolling were not satisfactory, as crevices were not entirely eliminated from the tube-header joints. Joint design No. 6 was completely free of cracks, and this demonstrated the effectiveness of keeping water out of the crevices by welding from the waterside of the joint. Joint No. 7 likewise produced no stress corrosion cracks. This experimental joint was of interest, as it demonstrated that the presence of boiler water in the crevice was not harmful provided the water was not allowed to boil.

A third boiler of standard design was operated on a test stand to determine the effect of eliminating chlorides from the water. The boiler was operated for 1013 hours. The initial feedwater was passed through an ion exchanger to reduce chlorides to about 0.1 ppm. A closed system was used, with the boiler water maintained at less than 10 micromhos during the entire operating period. Subsequent examination of the tube joints revealed freedom from stress corrosion cracks.

Finally, a fourth boiler of standard design was tested to determine the benefits to be obtained through oxygen control. This boiler was operated 2031 hours with alkaline-phosphate treatment, 2.5 to 3.5 epm alkalinity, and 530 ppm chloride. In addition, the system was scavenged of oxygen by maintaining a minimum of 100 ppm sulfite, added as sodium sulfite. Examination of tube joints from this boiler revealed no evidence of stress corrosion.

CONCLUSION

The laboratory program was not directed toward a systematic study of the fundamental nature of the stress corrosion phenomenon. However, the tests did contribute toward an understanding of the conditions under which the austenitic stainless steels will or will not be subject to stress corrosion damage. The experiments would appear to warrant the following general and specific conclusions regarding stress corrosion behavior in high temperature water environments.*

The stress corrosion of austenitic stainless steels in high purity water has not been explored as extensively as might be desired. However, the evidence indicates that stress corrosion cracking will occur very rarely, if ever, in major structural components of high purity water systems. Such components would be fabricated from mill annealed material, and stresses from fabrication and service, even if somewhat beyond the yield strength, should not lead to difficulty.

On the other hand, heavy cold working does seem to cause susceptibility to stress corrosion in high purity water, particularly oxygen bearing water. On this basis, austenitic stainless steels cannot be recommended for use as springs or any other specialty item in which the material is to be strengthened by intentional cold working.

The stress corrosion behavior of austenitic stainless steels in boiler water environments is a considerably more critical problem, mainly because of the chlorides which can be encountered in steam generation systems (especially naval boilers).

The austenitic stainless steels as a class seem to be susceptible to stress corrosion cracking in high temperature chloride water environments. Some compositions appear to be more resistant than others. Types 304, 316 and 347 are known to be among the more susceptible alloys. However, insufficient work has been done to enable listing the numerous alloys in a reliable order of relative resistance.

The stress corrosion is characterized by cracking of a predominantly transgranular nature. Sensitivity to intergranular corrosion is not necessary. However, sensitized alloys can fail by stress corrosion cracks following an intergranular path.

Transgranular stress corrosion cracks can vary in appearance from single relatively straight cracks to highly branched finger-like crack networks. Stress corrosion cracks usually start at corrosion pits, but it cannot be concluded that all environments leading to corrosion pits will also ultimately lead to stress corrosion cracks.

Stabilization of the austenite by moderate increase of nickel content (such as in Types 305 and 316) does not prevent stress corrosion, although it probably does increase resistence to cracking.

The thickness of a stress corrosion specimen has no noticeable effect on susceptibility to cracking.

Statically applied stresses as low as 5000 psi can cause stress corrosion of annealed steel in the proper environment. Residual stresses from tube rolling, cold forming, welding, and even cleaning with emery cloth, are sufficient to cause failure in environments highly conducive to stress corrosion.

The temperature of the environment does not have to be high. Information from both the tests and other sources would indicate that stress corrosion can occur at temperatures as low as the boiling point of water, and probably even lower. It is probable that stress corrosion is accelerated by increasing the temperature.

Stress corrosion can occur rapidly under highly conducive conditions. Speciments have been observed to fail within 20 minutes at 500°F (plus heating and cooling time).

Stress corrosion of austenitic stainless steels can occur in uninhibited water containing a moderately low chloride content. Specimens immersed in oxygen bearing water with 300 ppm chloride were readily cracked. Similar tests in chloride-free water did not result in cracks. The region below 300 ppm chloride has not been explored sufficiently to determine if some threshold chloride level exists (other than zero) below which stress corrosion will not occur with specimens exposed in the liquid phase.

The stress corrosion of austenitic stainless steels submerged in chloride bearing water of practical

*Many test details, as well as entire experiments in some cases, were not described in this article. Thus, a part of the conclusions may not be substantiated by the published results. Nevertheless, publication of all conclusions reached was considered worthwhile.

interest apparently can be prevented by alkaline-phosphate water treatment, provided the steels are in the mill annealed condition at the time of fabrication, and provided sensitization does not occur from welding or operating temperatures. Tests of Type 304 steel indicate that sensitization of unstabilized alloys can lead to failure by intergranular stress corrosion cracking in low oxygen alkaline-phosphate treated water, except possibly when the chloride content is kept very low.

Austenitic stainless steels exposed in the steam phase of chloride bearing water, and intermittently wetted (in the tests, by inversion of the pressure vessel), are susceptible to stress corrosion cracking at very low chloride contents. Cracks were produced readily under these circumstances with water containing as little as 1 ppm chloride.

It is not known whether the extreme sensitivity to cracking in the steam phase is due to some reactive characteristic of the vapor not present in the water, or to a concentration of the water constituents through the alternate wetting and drying process. However, the evidence favors the latter explanation.

Alkaline-phosphate water treatment does not inhibit the stress corrosion of austenitic stainless steels in the steam phase of boiler water.

Oxygen is a strong accelerator of stress corrosion of austenitic stainless steels in hot water environments. In fact, the evidence indicates that some oxygen is necessary for stress corrosion to occur. The necessary amount is small. It is believed that maintenance of oxygen at some value below 1 ppm (probably 0.5 ppm in critical areas) will provide reasonable assurance against stress corrosion failures at chloride levels likely to be encountered in steam generation equipment.

The maintenance of low oxygen might not be an entirely satisfactory method to prevent intergranular stress corrosion in unstabilized sensitized steel, such as Type 304. However, no problem of this sort is anticipated with stabilized steel, such as Type 347.

Vapor phase inhibitors offer some promise for the control of stress corrosion. It is probable that any successful inhibitor will have oxygen scavenging characteristics. Sulfite treatment has shown considerable promise.

The tests of the austenitic stainless steels were conducted, for the most part, under severe stress and environmental conditions. This was done purposely to detect susceptibility to stress corrosion within reasonable testing times. Thus, a high percentage of test specimen failures does not, in itself, indicate that service failures will occur in epidemic proportions. The principal value of the test work was to point to the need for extreme caution in the design and operation of equipment in which austenitic stainless steels are used in contact with high temperature water, and especially the steam phase of such water. Much can be accomplished by proper design and by operation of equipment within safe limits. The use of annealed steels, stress relief treatments, stabilized grades, low operational stresses, low chloride levels, low oxygen levels, and proper corrosion inhibitors are all important steps toward the elimination of stress corrosion hazards.

ACKNOWLEDGEMENT

The work and thoughts of many people have made this article possible, and the names are too numerous for individual acknowledgement. However, the authors wish to express appreciation to the U.S. Naval Boiler and Turbine Laboratory, Philadelphia, Pennsylvania, for operation of the auxiliary boilers, and to the Bureau of Ships for sponsorship and guidance.

Matters of opinion and interpretation expressed in this article are those of the authors and do not necessarily coincide with those of the individuals and organizations from whom the information was obtained.

REFERENCES

1. H. S. Rawdon, The Intercrystalline Corrosion of Metals, Ind. Eng. Chem. 19 (1927) 613.
2. Symposium on Stress-Corrosion of Metals, ASTM/AIME, 1944.
3. Metals Handbook, A.S.M. (1948).
4. H. H. Uhlig, Corrosion Handbook, John Wiley and Sons (1948).
5. R. A. Lincoln, Stress Corrosion in Stainless Steel, Paper Presented at A.I.S.I. General Meeting, May 26–27, 1954.
6. H. R. Copson, The Influence of Corrosion on the Cracking of Pressure Vessels, Welding Journal, 32 (1953) 755.
7. E. S. Dixon, Petroleum Refineries. The Book of Stainless Steels (E. E. Thum), 2nd Edition, A.S.M., (1935) 590.
8. M. A. Schiel, Some Observations of Stress-Corrosion Cracking in Austenitic Stainless Alloys, Symposium on Stress-Corrosion Cracking of Metals, ASTM/AIME (1944) 395.
9. R. Franks, W. O. Binder and C. M. Brown, The Susceptibility of Austenitic Stainless Steels to Stress-Corrosion Cracking, Symposium on Stress-Corrosion Cracking of Metals, ASTM/AIME (1944) 411.
10. C. Edeleanu, Transgranular Stress Corrosion in Chromium-Nickel, Stainless Steels, Jnl. Iron and Steel Inst., 173 (1953) 140.
11. H. Nathorst, Stress Corrosion Cracking in Stainless Steels, Welding Research Council, Bulletin No. 6, 1950.
12. G. A. Ellinger and H. L. Logan, private communication.
13. V. N. Krivobok, Discussion on Stress Corrosion of Stainless Steels, Symposium on Stress-Corrosion Cracking of Metals, ASTM/AIME, (1944) 426.
14. H. C. Fiedler, B. L. Averbach and M. Cohen, The Effect of Deformation on the Martensitic Transformation in Austenitic Stainless Steel, A.S.M. Preprint No. 30, (1954).
15. J. T. Waber, Discussion on Stress Corrosion of Stainless Steels, Symposium on Stress-Corrosion Cracking of Metals, ASTM/AIME, (1944) 426.
16. F. W. Davis, Discussion of Stress Corrosion of Stainless Steels, Symposium on Stress-Corrosion Cracking of Metals, ASTM/AIME, (1944) 429.
17. J. J. Harwood, The Influence of Stress on Corrosion, Part 2, Corrosion, 6 (1950) 290.
18. R. B. Mears and R. H. Brown, Causes of Corrosion Currents, Ind. Eng. Chem., 33 (1941) 1001.
19. D. K. Priest, A. Study of Stress Corrosion, Motion Picture Film, The Pfaudler Company.
20. R. B. Mears, R. H. Brown and E. H. Dix, Jr. A Generalized Theory of Stress Corrosion of Alloys, Symposium on Stress-Corrosion Cracking of Metals, ASTM/AIME (1944).
21. H. L. Logan, Film-Rupture Mechanism of Stress Corrosion, Jnl. Res. Nat. Bur. of Stds., 48 (1952) 99.

22. T. P. Hoar and J. G. Hines, The Corrosion Potential of Stainless Steels during Stress Corrosion, Jnl. Iron and Steel Inst., 177 (1954) 248.

23. F. W. Davis, Stress Corrosion in a Stainless Steel Compressor, Trans. A.S.M., 42 (1950) 1233.

24. F. W. Davis, private communication.

25. J. A. Collins, Effect of Design, Fabrication and Installation on the Performance of Stainless Steel Equipment, Corrosion, 11 (1955) 27.

26. D. J. DePaul, Corrosion Engineering Problems in High Purity Water, paper presented at March 1955 meeting of National Assn. of Corrosion Engineers.

27. Based partly on data furnished by Westinghouse Atomic Power Division, private communication.

28. Based on data furnished by Westinghouse Atomic Power Division, private communication.

On April 11, 1900, the Navy accepted its first submarine, the USS HOLLAND, named for its builder, John Phillip Holland.

* * *

Before World War II carriers had approximately 4,500 kilowatts of ship's service power; now they have 13,200 kilowatts.

* * *

Launched on April 23, 1917, the USS NEW MEXICO was the first battleship to be propelled by electricity.

* * *

The first paddle-wheeled steam warships were the USS MISSISSIPPI and the USS MISSOURI in 1841.

FRANK E. CLARKE

BREATH OF THE FLEET
A STORY OF NAVAL GAS EQUIPMENT

THE AUTHOR

graduated from Western Maryland College in 1935 with degrees in chemistry and education. Studied advanced physical chemistry for one year at University of Maryland and taught chemistry for four years before entering the Boiler Water Section at the E.E.S. Chemical Laboratory in March 1941. He became head of the Boiler Water Section in 1942, Head of the Chemical and Physical Branch in 1946 and Head of the Process Branch, Chemical Engineering Laboratory in 1951. Evaluation of gas equipment for the Fleet is a major function of the Process Branch.

WHEN COLERIDGE penned the immortal lines "Water, water everywhere nor any drop to drink," little did he dream that time would add the sequel: air, air everywhere but not enough to breathe. Paradoxically, the latter was a penalty for creation rather than for destruction—creation of planes and submarines capable of traveling where human respiration alone would not suffice. There came a time when bottled oxygen no longer was adequate for the aircraft carrier and the submarine could not depend entirely on solid chemicals for carbon dioxide absorption.

Fortunately, the modern mariner did not have to depend entirely on fate to overcome his plight, as did the ancient mariner. Government research and development programs provided a very practicable and effective artificial respiration for the Fleet. Compact shipboard plants now separate atmospheric oxygen to sustain the carrier pilot and yield by-product nitrogen for use in fire prevention. Other plants have been built to absorb carbon dioxide exhaled by submarine crews. Dreams of preparing oxygen from sea water for continuous submergence are approaching reality. In a single decade, gas processing has established itself as a vital function of the Fleet.

OXYGEN FROM CHEMICALS

In the relatively quiet years before World War II, the surface fleet took most of its breathing oxygen directly from the atmosphere or oxygen bottles. Synthetic oxygen was primarily an emergency item for rescue work, firefighting and certain limited aircraft uses (bail out, etc.). It is not surprising that oxygen producing chemicals were considered for such uses.

The Navy's interest in chemical oxygen sources carried over into the war years with rather thorough studies of both one-shot and regenerative types. These never replaced bottled oxygen completely and they never were major sources of aviators' breathing oxygen. On the other hand, chemical generators still are the principal sources of emergency breathing oxygen on surface ships.

Non-regenerative Chemical Sources—Non-regenerative oxygen sources were attractive because they required relatively simple, expendable equipment. Most work centered around alkaline peroxides and chlorates since these are the only inexpensive chemical sources of oxygen with favorable reactions. The decomposition of perchlorates to yield oxygen first was described in 1785 and is a process well known to the high school chemistry student. Oxygen masks using alkali peroxide date back at least to 1904. However, the real development work on both oxygen sources was conducted by the Naval Research Laboratory in the years immediately prior to World War II and continued by that Laboratory and the National Defense Research Council program during the emergency.

Peroxide—Theoretically, hydrogen peroxide is an ideal source of breathing oxygen since it decomposes readily and yields water as the only by-product. From the standpoints of weight and space requirements, only 90% hydrogen peroxide is practicable. This has not been used to any appreciable extent because of supply and storage problems. However, it now is being considered for submarine use.

Sodium peroxide and potassium tetraoxide, both yellowish powders, are the most productive, reasonably stable forms of peroxide oxygen. Both require water for oxygen generation as shown by the following equations:

$$2\,Na_2 + 2\,H_2O \rightarrow 4\,NaOH + O_2$$
$$2\,K_2O_4 + 2\,H_2O \rightarrow 4\,KOH + 3\,O_2$$

Both reactions liberate heat, but the first produces between 4 and 5 times as much per gram molecular weight as the second and consequently requires considerably more cooling.

Since these reactions require water, they are adaptable to the well-known Kipp type generator in which gas generation stops and starts automatically as the draw-off and consequent pressure change raises and lowers the water level in the generator. The plan of a typical Kipp generator is shown in Figure 1. Units of this type have been used by the Navy for generating oxygen up to 100 psi for underwater cutting and similar small scale uses.

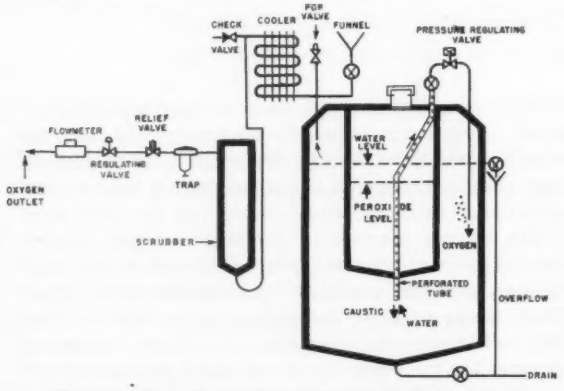

Figure 1. Kipp Type Peroxide Oxygen Generator.

Another interesting use of peroxide, made possible by the requirement for water in the reaction, is the rebreather-type face mask, like the Navy's C-K rebreather diagrammed in Figure 2. Moist air exhaled into the peroxide container releases oxygen in proportion to the rate of breathing. Respiration continues in a closed cycle until the breathing bag becomes inflated, at which point a bleed off valve wastes sufficient gas to keep the system in equilibrium.

Original peroxide breathers suffered from the fact that external heat was not available to start the reaction in cold weather. The Navy first overcame this problem by adding an electric heater but later switched to a chlorate starting candle detonated with a grenade primer. This self starter provided both heat and oxygen.

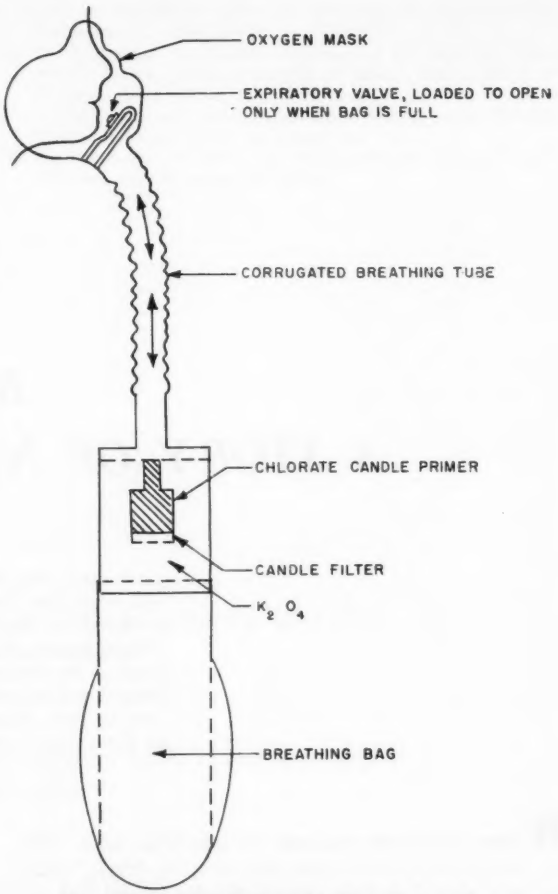

Figure 2. Navy C-K Peroxide Type Rebreather.

The C-K peroxide rebreather was designed primarily for long shelf life and easy starting. A pull of the starting tab at the top of the cannister (corresponding to the rip cord of a parachute) automatically released the connector for the face mask, fired the chlorate candle, released the breathing bag and opened the cannister to the closed respiration cycle.

The automatic exhaustion indicator was the most ingenious feature of the rebreather. Absorption of carbon dioxide by the caustic by-product (KOH) continued beyond the oxygen generating reaction and thereby reduced the overall volume of gas in the closed cycle at the end of the cannister's life. This resulted in partial collapse of the bag and warned the operator to switch to a new cartridge.

Chlorate Candle—This somewhat more compact, but less efficient, emergency oxygen generator was used by the Germans as early as 1930 in mine rescue work and was tried by the BritishAdmiralty in 1933 for submarine use. Both the British and the Japanese were conducting further experiments in 1942 and by 1943 the U. S. Naval Research Laboratory had entered the field. Chlorate generators are based on the fact that properly catalyzed potassium or sodium chlorate will undergo the following reaction when

heated. This is identical with that of the chlorate starting candles in the peroxide generators:

$$2KC\ell O_3 \rightarrow 2KC\ell + 3O_2$$

or

$$2NaC\ell O_3 \rightarrow 2NaC\ell + 3O_2$$

The chlorate candle finally developed by industrial contracts had approximately the composition shown below.

	Per Cent
$NaC\ell O_3$	81
Fe (iron powder)	10
BaO_2 (barium oxide)	3
Powdered fiberglass	6

This mixture was cast in greenish, lava-like candles approximately 10" long and 1.5" in diameter. When detonated with a grenade-type primer, reaction of initial oxygen with iron generated sufficient heat to perpetuate decomposition of the chlorate. Barium oxide improved the reaction but was included primarily to absorb any chlorine released by side reactions.

The candle and igniter were packaged in a cannister of the type shown in Figure 3. This included a rip cord to start the grenade primer, a heat absorbing filter to reduce the hot gas to breathing temperature, a pinwheel spinner to indicate flow and a ballast tank "economizer" which allowed the generated oxygen to mix with inhaled and exhaled air and thus minimize oxygen waste. The cannister was covered with a temperature sensitive paint which followed the level of burning by changing color and thereby indicated exhaustion of oxygen supply.

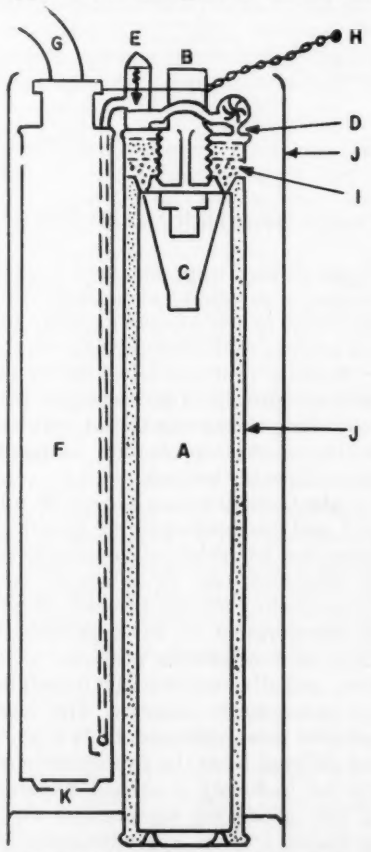

Figure 3. Chlorate Oxygen Generator.
(a) Chlorate Candle, (b) Grenade Igniter, (c) Ignition Cone, (d) Oxygen Take Off, (e) Diaphragm Lance, (f) Economizer, (g) Face Mask Tube, (h) Starting Cord, (i) Heat Absorber, (j) Insulation, (k) Oxygen Diluter Valve, (l) Oxygen Inlet to Economizer.

The chlorate candle, like the peroxide cannister, was an emergency item intended for use in case of blow outs in pressurized plane compartments, occasional high altitude excursions of low-level planes like the B-25, bail out units, fire fighting and rescue work. Modern counterparts of both systems still are in regular use as emergency equipment.

Regenerative Chemical Sources (Salcomine)—Explorations in this field were attempts to reproduce, with man-made equipment and appropriate chemicals, the well-known oxygenation-deoxygenation cycle carried on by hemoglobin in living organisms. The relatively elaborate equipment and low efficiency of process finally obtained left little doubt that nature had done a better engineering job.

Of the numerous chemicals tried, the cobalt chelate shown in Figure 4 was the most promising oxygen carrier. This powdery crystalline material has the property of absorbing oxygen at low temperature and high pressure and discharging it under the opposite conditions. Various methods of exposing it to the generating and degenerating atmospheres were tried. One consisted of suspending the chemical in oil and pumping it through the atmosphere, another involved circulating the dry powder with a screw-type conveyer, and a third passed the atmosphere through packed beds of chemical. The last system proved to be the most practicable. The chemical was packed as large granules or pellets in heat exchanger shells which provided either cooling during oxygenation (regeneration) or heating for generation of oxygen.

The Arthur D. Little Co. made a prototype shipboard model based on the heat exchanger principle. Its exchanger is shown in Figure 5. The unit was installed on the Destroyer Tender USS *Prairie* in 1943 following tests at the Engineering Experiment Station. Operation of the vessel in tropical waters

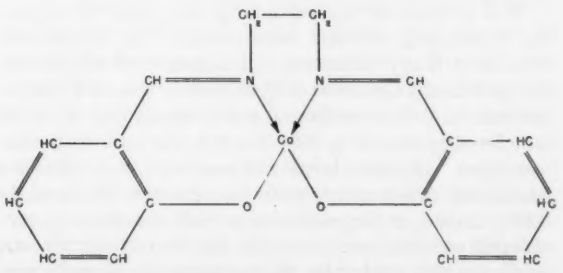

Figure 4. Chemical Structure of Salcomine Oxygen Carrier.

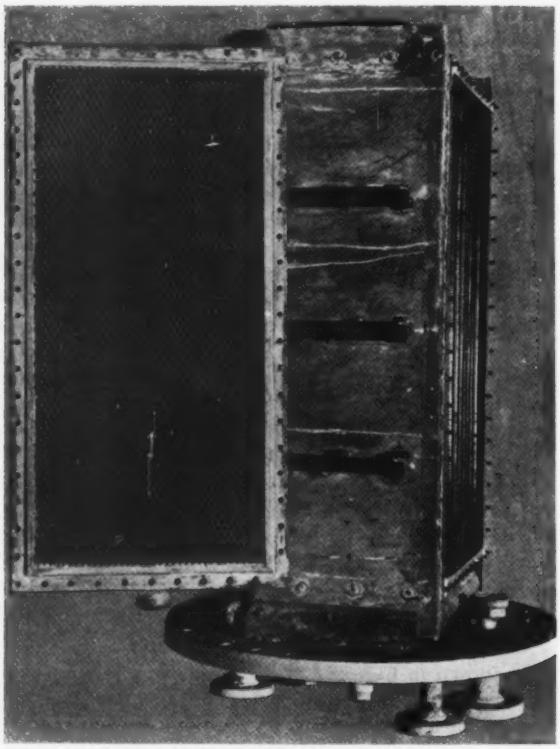

Figure 5. Salcomine "Oxygen Exchanger."

showed that sea water cooling alone was inadequate and that the Salcomine deteriorated more rapidly than expected. About 4½ pounds of oxygen could be obtained from each pound of chemical during its useful life. While this was better from the standpoint of weight and space than carrying 4½ pounds of oxygen in a heavy metal bottle, the high cost of Salcomine and problems of supply were prohibitive. It is interesting to note that the Commanding Officer of the USS *Prairie* considered the system promising despite its problems.

ORIGIN OF THE LIQUID AIR PLANT

Major changes in Fleet operations during the war (both real and projected) boosted synthetic oxygen from an emergency item to an item of large scale general use. The liquid air plant was the logical answer to this new demand.

The process of concentrating atmospheric oxygen by liquefying air and fractionating the liquid was neither a Navy invention nor a recent development. In 1877 Louis Cailletet of France and Raoult Pictet of Switzerland first produced small quantities of liquid air. During the early 90's, Dewar, for whom the Dewar flask (thermos bottle) is named, was conducting elaborate experiments with liquid air in England. In 1895, Linde, a German, conceived the idea of producing oxygen commercially by liquefying air and applying the principles of fractionation already well known in the alcohol industry. The famous Linde cycle was perfected during the same year. An alternate cycle by Claude (French) followed close on its heels. By the turn of the century, liquefaction of air and separation of its components were established industrial processes but the Navy had virtually no use for them at that time.

BASIC AIR LIQUEFACTION CYCLES

To follow the development of the Navy oxygen-nitrogen plant, it is necessary to understand at least the basic principles of the Linde and Claude cycles. Virtually all modern industrial and military air liquefiers are modifications of these systems.

Linde Cycle — This process is based on the well known Joule-Thompson gas expansion principle of refrigeration. This consists of expanding compressed gas through a valve or orifice and capitalizing on the temperature drop in the expanding gas. The Linde cycle in its simplest form is shown diagrammatically in Figure 6. It includes an air compressor, heat exchanger, expansion valve and vessel to collect the

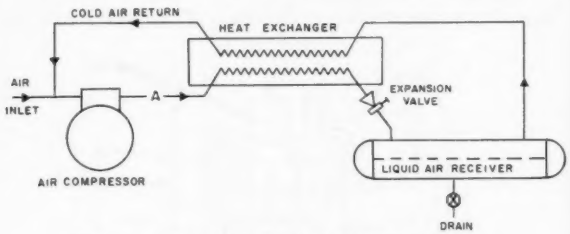

Figure 6. Simple Linde Air Liquidifier (1895).

liquefied gas. Filters, traps, etc. have been eliminated in the interest of simplicity. Compressed air traveling in the direction of the arrows expands through the valve and returns to the compressor via the heat exchanger, thereby progressively cooling the system. The continuous process of precooling in the exchanger and recooling in the expansion valve eventually reduces the air to liquefaction temperature and liquid air collects in the tank.

Such a plant, compressing air to 200 atmospheres (3000 psi) and discharging liquid product at atmospheric pressure, has relatively poor efficiency. However, its efficiency can be increased considerably either by precooling the compressed air with supplementary refrigeration or by expanding the major part of it to an intermediate pressure, of 40 or 50 atmospheres, and allowing only the liquefying fraction to fall to atmospheric pressure. The second Linde cycle included these refinements. It is shown in Figure 7 and differed from the simple cycle of Figure 6 primarily by including a second expansion valve. Most of the precooled compressed air expanded through Valve 1 from approximately 200 atmospheres to 40 atmospheres before it re-cycled to the compressor via the heat exchanger. A much smaller portion expanded through Valve 2 either liquefying and collecting in the reservoir or returning to the compressor by the alternate route.

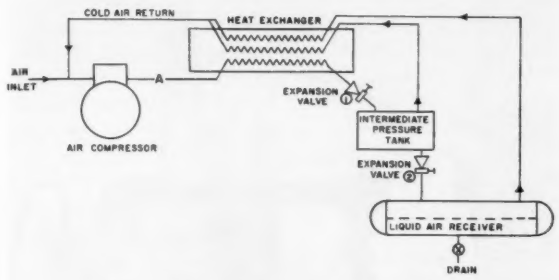

Figure 7. Two Pressure Linde Air Liquidifier.

Claude Cycle — This is based on the thermodynamic principle that compressed gas loses heat when used to drive a reciprocating engine or a turbine. The cycle in its simplest form consists of a compressor, expansion engine, heat exchangers and liquid air collector. However, it is impracticable to liquefy air completely by this simple cycle. The efficiency of the expansion engine becomes increasingly lower as liquid air temperature is approached and no engine will function properly with liquid air condensing in its cylinder. For these reasons, the actual Claude process is a combination of Joule-Thompson (valve) expansion and expansion engine refrigeration.

A simplified flow diagram is shown in Figure 8. Compressed air passes through a primary heat exchanger and splits into two streams for the two cooling processes. One passes through two other heat exchangers and the expansion valve into the liquid air collector, from which vapor returns through the three heat exchangers. This part of the cycle is identical with the Linde cycle except for the much lower operating pressure. The second stream passes through the expansion engine and the cool engine exhaust returns to the compressor via the first two heat exchangers. Claude recommended that about 20% of the air be expanded in the valve and 80% in the engine and that the intake temperature to the engine be approximately -80°C. This process has the advantage of good efficiency at relatively low operating pressures. The Heylandt cycle, sometimes mentioned as a third basic cycle, is nothing more than a Claude cycle modified to obtain the optimum combination of valve and engine expansions.

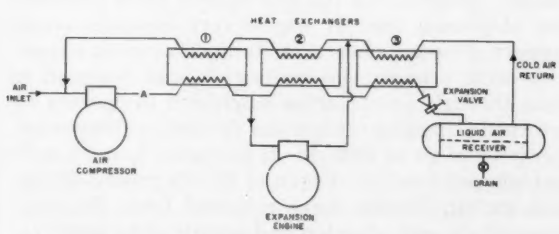

Figure 8. Simple Claude Air Liquidifier.

FRACTIONATION OF AIR

Oxygen Separation—Single Column Plant

The step from liquid air to liquid oxygen was a logical one in view of the commercial demand for oxygen and the well established principles of fractional distillation in the alcohol industry at the turn of the century. The original Linde single column liquid oxygen plant of 1902 was a simple form of oxygen separation equipment. Its principle is shown in Figure 9. Compressed air, with moisture and carbon dioxide

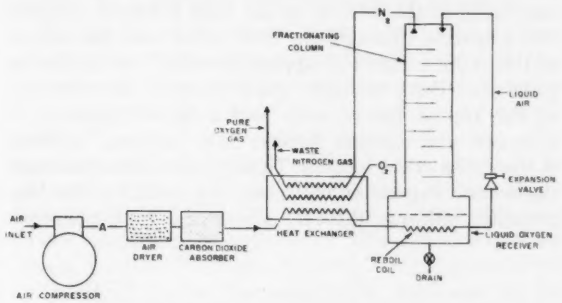

Figure 9. Original Linde Liquid Oxygen Plant (1902).

removed, passed through the primary heat exchanger and the heat exchanger coil in the reboiler sump of the fractionating column to the expansion valve, which transferred it primarily as liquid air to the top of the column. The liquid cascading over the plates to the sump became richer in oxygen by reaction with vapors rising in the column. A part of the oxygen was drawn as liquid from the sump. The remainder returned as gas with the nitrogen via the primary heat exchanger to complete the refrigeration cycle.

This single column plant produced high purity liquid oxygen but was incapable of producing liquid nitrogen. This deficiency alone was not particularly important in view of the lack of market for nitrogen at that time. On the other hand the relatively large amount of oxygen entrained by the waste nitrogen seriously reduced plant efficiency for oxygen production. For this reason the double column oxygen-nitrogen plant soon was developed.

Double Column Oxygen-Nitrogen Plant

If it were not for unfavorable temperature relationships, the 80/20 mixture of nitrogen and oxygen in air could be separated at atmospheric pressure by introducing it at the proper point in a fractionating column equipped with an evaporator coil at the bottom and a condenser at the top. Part of the oxygen would collect as liquid in the evaporator sump and part of the nitrogen would liquefy in the condenser. Thus a single column would serve to prepare both constituents in liquid form. Unfortunately, the temperature of liquid nitrogen is below that of either liquid air or liquid oxygen at the same pressure, so

that neither can be used for refrigerating the nitrogen condenser in such a simple plant. Linde overcame this problem by devising a two-column plant and introducing liquid air to one column above atmospheric pressure. Gaseous nitrogen separated from this air could be condensed with liquid oxygen from the second column operating at atmospheric pressure.

The perfected version of this system appeared in 1910 and still is used with no basic change. A skeleton flow sheet is shown in Figure 10. Precooled compressed air passes through the evaporating coil in the sump at the bottom of the high pressure column and expands through the first valve into the center of the same column at approximately 5 atmospheres pressure. Pure nitrogen gas collects in a condenser at the top of the column and a liquid mixture of nitrogen and oxygen (about 35% oxygen) collects in the sump at the bottom. This mixture flows through the second expansion valve into the middle of the low pressure column, directly above the high pressure

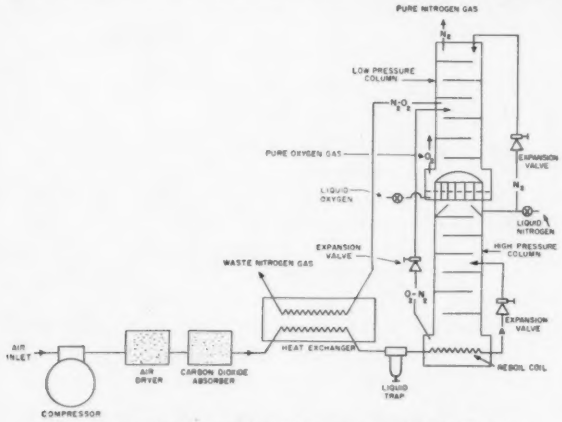

Figure 10. Linde Double Column O_2-N_2 Plant (1910).

column. Stripping in the low pressure column yields pure liquid oxygen in the sump around the condenser. Part of the pure nitrogen gas at the top of the high pressure column is liquefied and collects in a trough or funnel immediately below. From here it is expanded to atmospheric pressure through a third valve and used to rectify the oxygen-nitrogen mixture in the low pressure column. Pure gaseous nitrogen is withdrawn at the top of this column and either pure liquid oxygen or pure gaseous oxygen can be withdrawn from its sump.

The system is extremely flexible so that both products can be withdrawn as either gas or liquid, the yield of one phase being increased at the expense of the other. The same general system of rectification can be used with the Claude expansion engine method of refrigeration and with supplementary refrigerating cycles.

EVOLUTION OF THE NAVY OXYGEN-NITROGEN PLANT

Despite the long history of oxygen-nitrogen plants, the Fleet had none prior to World War II. In the fall of 1940, more than a year before Pearl Harbor, tenta-

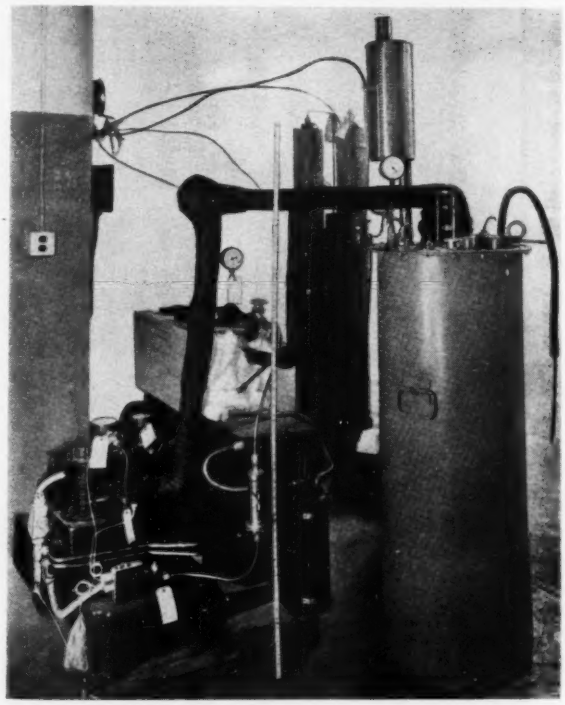

Figure 11. Keyes Prototype Submarine Breathing Oxygen Plant.

tive plans were made for a new type of submarine which required large quantities of oxygen for use as "secondary fuel" in its diesel engine propulsion system. A compact shipboard plant capable of generating oxygen when the vessel surfaced appeared to be the logical answer. By the latter part of 1941 need had also developed for breathing oxygen plants on submarines and surface ships as well as in advanced bases.

The problem of developing these plants was turned over to the infant National Defense Research Council (formed during the summer of 1940), specifically to Section 11.1 which concentrated its efforts primarily on the production of oxygen for military services. The plants described below resulted from these efforts.

Keyes Liquid Oxygen Plant

The Keyes submarine breathing oxygen plant shown in Figure 11 was the first Navy product of the NDRC program and the first oxygen plant proposed for shipboard use. It was a very compact liquid oxygen generator based on Joule-Thompson expansion with primary gas cooling. It was designed to pass through a submarine hatch and to operate on a torpedo charging compressor furnishing 300 pounds per hour of air at 3000 psi. It produced from 15 to 18 pounds per hour of oxygen at 98+% purity. Water and carbon dioxide were removed from the compressed air with alumina and caustic soda traps, respectively. There was also an activated carbon filter

for removing last traces of contamination. An EES report on this Keyes Plant was made in March 1943.

After successful trial of the prototype Keyes plant, four somewhat more elaborate production models were producted. Two of these were sent to Great Britain for test and two were retained for tests in this country. This plant weighed approximately 1100 pounds and could make liquid oxygen in 45 to 60 minutes after lighting off. It performed very reliably in prototype tests.

A new experimental Keyes plant with a liquid oxygen pump and the capacity for producing gaseous oxygen at high pressure followed the unit mentioned above. A prototype based on this design was made and operated satisfactorily. Later a production model was designed with a rotating column for shipboard use. It was to occupy 3'x5' floor space, have a 7' ceiling and produce 95.5% oxygen in either liquid or gaseous form. Two such units were being constructed at the end of World War II.

Despite the promising performance of the several Keyes plants, none was actually used on shipboard. The end of the emergency temporarily reduced the demand for breathing oxygen plants and larger plants stole the show when the demand was renewed. As this paper is being prepared, the EES Gas Section is testing one of the final production models of the Keyes plant because of renewed interest in small oxygen generators.

Collins Gaseous Oxygen Plant

Development of this Navy prototype paralleled that of the Keyes submarine unit. A simplified flow plan is shown in Figure 12. It was a very small, low pressure unit operating on 150 psi air, weighing 165 pounds, less compressor, and occupying only 9 cubic feet of space. It combined engine and valve expansion principles. A novel feature was the use of alternating heat exchangers as freeze-out traps for water, carbon dioxide and hydrocarbons. This eliminated the need for chemical absorbers. Contaminants were evaporated periodically by reversing gas flows and were carried away in the waste nitrogen stream. The product was 95.5+% gaseous oxygen. The official NDRC report indicates that quantities of these plants were used by the Navy.

Kellogg Plants

The Kellogg Company's part in the Navy's gas program started with an NDRC Conference in January 1942. The general program outlined for the military services at that time indicated Navy need for a shipboard unit capable of producing about 600 CFH of high purity cutting and welding oxygen at 150 psi and a much larger shipboard unit for producing up to 4000 pounds per hour of 95-96% liquid oxygen for submarine propulsion. The smaller shipboard unit originally was intended to be a regenerative chemical type already mentioned (Salcomine); however, this idea was abandoned the following month because weight and power consumption appeared to be excessive as compared with mechanical processes.

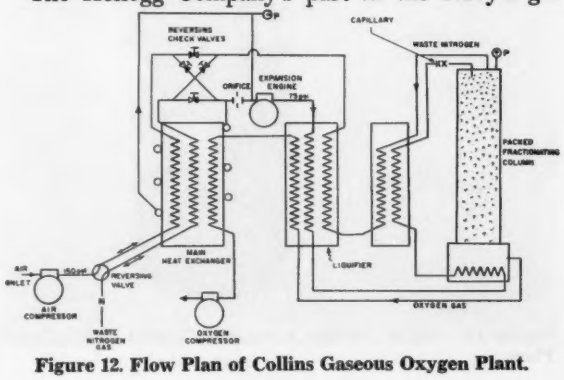

Figure 12. Flow Plan of Collins Gaseous Oxygen Plant.

Within the next several years, the Kellogg Company investigated numerous air liquefaction and fractionating systems identified with a series of M codes. Two of these, the M5 and M6, were designed specifically to meet Navy shipboard requirements. The company did not consider either of the plants to be as good as their M7 gaseous oxygen, low pressure unit developed for the Air Force. However, the Navy concluded in September 1946, after extensive trials, that the M5 plant fulfilled Navy shipboard requirements better than any other produced by the NDRC program.

M5 Plant

This was a low pressure plant (100 psi) using a combination of 25% valve expansion and 75% turbine expansion. The air cleaning system was rather elaborate. It included sintered metal filters, centrifugal traps, paper filters, cloth filters, silica gel absorbers, and metal packed "regenerators." Gas flow in the "regenerators" was reversed at 3 minute intervals so that they alternately carried refrigerated air and returned waste nitrogen gas. During air flow, moisture, carbon dioxide and organics collected on the metal packing. Nitrogen flow evaporated the contaminants and prepared the regenerators for the next freeze-out period.

The fractionation system was a conventional type but included a packed column (Steadman type) rather than a tray column.

The original M5 was designed to produce 400 pounds per hour of liquid oxygen of 95% purity without chemical cleanup and despite rock and roll of shipboard service (6 cycles per minute to 15° from vertical). It was intended for intermittent operation of 8 to 10 hours on and 14 to 16 hours off. The goal of intermittent operation was achieved, but the packed fractionating column was unsatisfactory for inclined operation. Another serious objection was clogging of the regenerators after 6 to 12 hours of operation. The performance of the turbo expander was very satisfactory.

On the basis of experiments with the first M5 units, Collins alternating heat exchangers were substituted for the regenerators and the packed column was replaced with an improved tray type. Return nitrogen coils were soldered around the cold tubes of the reversing heat exchangers (nitrogen unbalancing stream) to hasten carbon dioxide ice removal. These

changes improved oxygen purity and made it possible to operate for 10 days or more without freeze-up.

In August, 1942, the Bureau of Ships authorized the Engineering Experiment Station to test the improved M5 plant with the assistance of Kellogg personnel. This plan never materialized but the plant was set up at the University of Pennsylvania and operated extensively during the years 1944 to 1947. Government sponsored development work on the M5 finally was cancelled in September 1947 because of growing industrial interest in low pressure plants of the same type, and consequent industrial development programs.

Installation of the M5 on submarines never became a reality, partly because advances in propulsion techniques reduced the need for a large oxygen supply but also because the relatively large size of the unit (15'x17'x15') made it impracticable.

M6 Plant

The M6 Kellogg plant was intended to meet the same general shipboard specifications and requirements as the M5. The primary difference was that it operated in a medium pressure range of 600 psi. This permitted the use of readily available high-speed reciprocating air compressors and conventional reciprocating expansion engines instead of the custom made auxiliaries required by the M5. The M6 used alternating heat exchangers and operated satisfactorily for continuous periods up to 72 hours.

This shift toward high pressure cycles was a step toward modern shipboard oxygen-nitrogen generators, but the M6, like the M5, never saw shipboard service and never really progressed beyond the prototype stage.

Arthur D. Little-Latham Plant

This plant was developed concurrently with the Keyes plant and for one of the same purposes, replenishing oxygen in submarine atmospheres. It was rated at 20 to 25 pounds per hour of liquid oxygen. It differed from the Keyes in using a capillary tube instead of an expansion valve, and double shell vacuum insulation (Dewar type) instead of packed insulation. The capillary expander was said to be easier thawed when plugged with CO_2 ice. The Latham plant proper was only 8" in diameter and 5' high. Its core is shown in Figure 13.

This plant operated satisfactorily in experimental tests, but its vacuum insulation soon broke down and its fractionation was poor because of basic deficiencies in the packed column. It never progressed beyond the experimental stage.

National Cylinder Gas Co. Oxygen Plant

This was the second mechanical gas plant tested at the Experiment Station during the concentrated period of development in the early years of the war. The test was authorized in August 1942 and reported on April 15, 1943. This was a 3000 psi plant occupying 7'x15' floor space and 9' height and weighing approximately 12,000 pounds. It included both chemical and physical cleanup systems. The liquefaction and fractionation systems were straight Linde type. The column was designed to rotate at 200 rpm.

At the maximum free air input of 6900 CFH this plant produced about 40 pounds per hour of liquid oxygen at a purity of about 98.4%. Both its large size

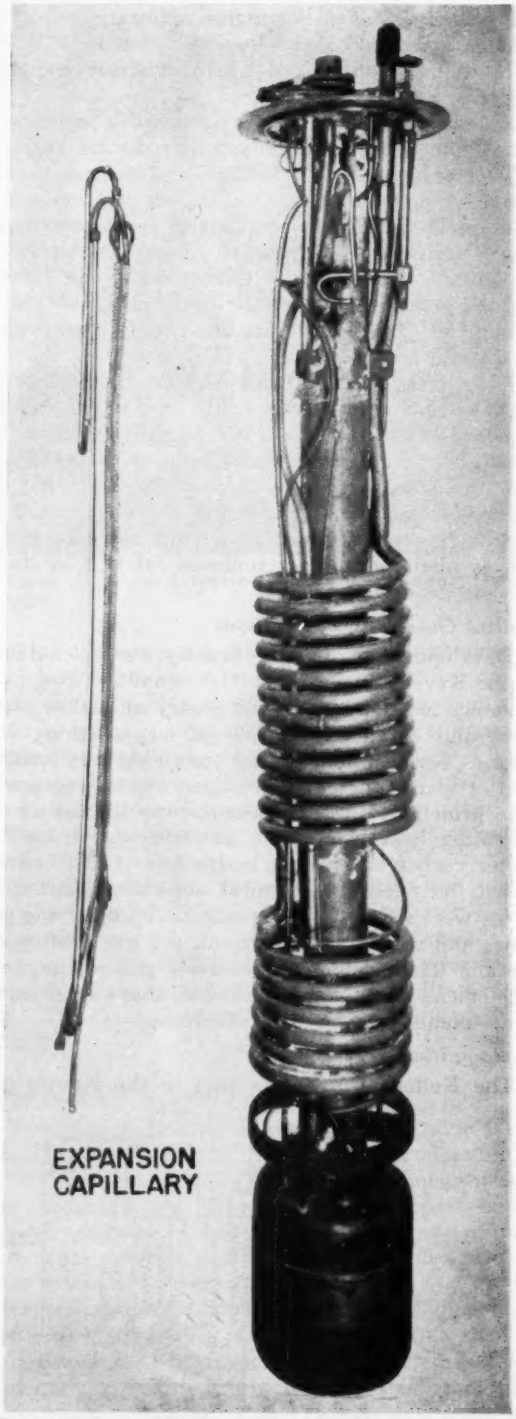

Figure 13. Core of Latham Submarine Type Liquid Oxygen Plant.

and its chemical cleanup feature made it unattractive for Fleet use.

Linde Advance Base Plant

Navy advance base liquid oxygen plants developed along with the early shipboard models; however, very little mention is made of them in official NDRC Reports. Several were purchased from Linde Air Products Company during World War II and most of these eventually were sent to universities for research projects.

In April 1953 the Experiment Station obtained one of these plants from the Illinois Institute of Technology for general evaluation. It is shown in Figure 14. This was a Claude cycle plant using an expansion engine loaded with an air compressor. The oxygen producer, called an interchanger, consisted of a series of heat exchangers, filters and a plate type distillation column. Compressed air was supplied at approximately 275 psi. The plant was simple to operate and capable of producing 550 CFH of liquid oxygen at a purity of 99.5% or better. On the other hand it required approximately 50% more horse power per cubic foot of liquid oxygen produced than Navy plants now available.

Badger Oxygen Plant (First Shipboard)

The E. B. Badger Company entered the Navy gas field with a production model shipboard liquid oxygen plant based on a skid-mounted, 400 CFH gaseous oxygen plant originally designed by the Air Reduction Co. for the Army Engineers and the Air Force. The Navy plant differed from the original model in having a packed, rotating column instead of a plate column and in using regular production line reciprocating compressors instead of special Air Reduction Co. compressors.

In discussing original trials of this 2000 psi plant, the Badger Co. was far from complimentary and labelled the results "extremely unsatisfactory and inconsistent." Despite this conclusion, improved models were used in advanced bases during the war and were the first ever to be installed on Navy ships. The first shipboard installation was made on a repair ship (USS *Vulcan*) about 1946. Two carriers, USS *Antietam* and the USS *Valley Forge*, received similar plants approximately two years later. The liquefaction and fractionation systems of this plant were the first to be taught in the Navy Gas School at Norfolk Naval Shipyard.

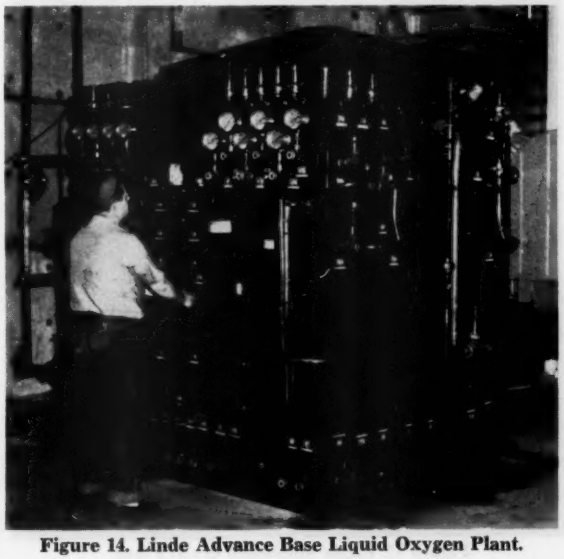

Figure 14. Linde Advance Base Liquid Oxygen Plant.

A considerable number of advance base models of the Badger plant were purchased by the Navy during the War, of which at least 20 presently are stored in Naval supply depots. The Station conducted "post mortem" engineering evaluation tests on one of these plants in the fall of 1953, soon after improved gas plants discussed later in this article had been accepted as principal shipboard units.

Figure 15 shows this Badger Plant. The 2000 psi compressed air passed through soda lime, low temperature oil- and water-separators, and silica gel driers before reaching the waste-nitrogen heat exchangers. From here, it passed through a refrigerating system and into the reboiler coil where it liquefied and flowed to the top of the packed rectifying column via an expansion valve. Liquid air cascading down the column terminated as liquid oxygen in the reboiler section while cold waste-nitrogen leaving the top of the column passed back through the heat exchangers. This cycle, when operated with the maximum air supply available at the test site (3800 CFH), liquefied about 470 CFH of 99.5% oxygen. The rated capacity was 484 CFH (40 pounds of liquid).

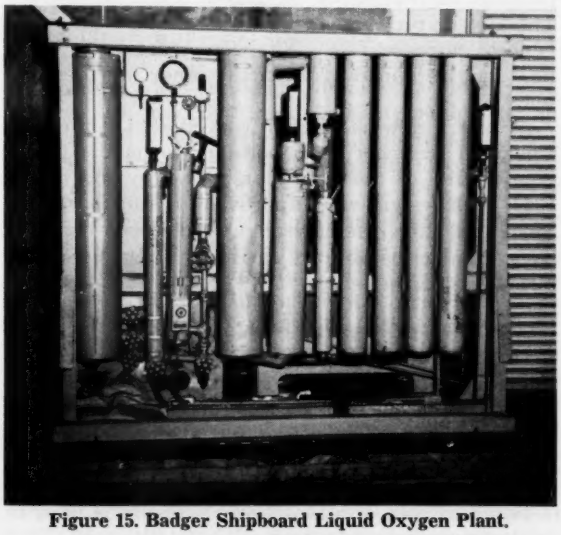

Figure 15. Badger Shipboard Liquid Oxygen Plant.

Except for its major deficiency of requiring chemical clean-up, the Badger plant has the advantages over modern shipboard oxygen-nitrogen plants of shorter downtime, easier operation, compactness, lightness of weight and ready accessibility of components. However, it produces no high purity nitrogen gas which now is almost as important as oxygen for certain modern shipboard applications.

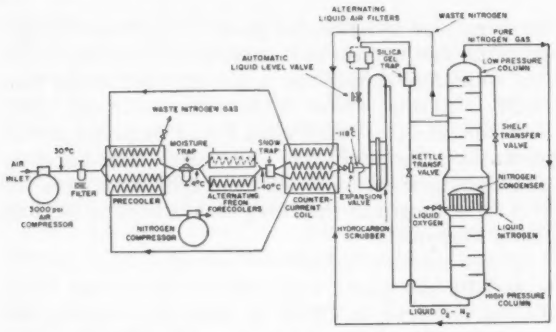

Figure 16. Flow Diagram of Linde Shipboard O_2-N_2 Plant (1950).

MODERN SHIPBOARD OXYGEN-NITROGEN PLANTS

The end of World War II virtually stopped contract development work on the wartime plants already described, but it did not kill the Navy's interest in shipboard gas production. The Bureau of Ships started negotiations almost immediately with Linde Air Products, Inc. and Air Products, Inc. for improved, compact high-pressure oxygen-nitrogen generators. The oxygen product was intended for breathing and general purpose uses. Nitrogen generation was a new feature aimed at replacing other inerting systems.

In 1950, a new gas section was created in the EES Chemical Engineering Laboratory to handle prototype testing of the new plants, and by the fall of 1951, both designs were approved for shipboard use. Since that time, the new plants have been installed on a number of aircraft carriers. They have performed as expected.

Linde Shipboard O_2-N_2 Plant

The basic flow sheet and general appearance of the Linde shipboard plant are shown in Figures 16 and 17. This is a typical Linde high-pressure cycle using supplementary refrigeration and a relatively elaborate series of heat exchangers, traps, filters and separators. It employs dual column fractionation wherein liquid oxygen at atmospheric pressure is used to condense compressed nitrogen (5 atmospheres).

The 3000 psi air supply passes through a felt packed primary oil filter, a nitrogen refrigerated precooler and a packed moisture separator (condenser) to one of a pair of alternating refrigerated forecoolers. Periodically, the forecooler stream is switched and accumulated ice is thawed with hot (compressed) gas.

From the forecooler —40°C air passes through a snow trap, a nitrogen refrigerated countercurrent cooler and the primary expansion valve to the "hydrocarbon scrubber." This separates the —118°C air into liquid and gas phases, leaving solid contaminants, like carbon dioxide snow and certain hydrocarbons in the liquid phase. These are removed by a pair of alternating, porous stone filters periodically regenerated with steam-heated compressed air. The filtered liquid air flows to the low pressure fractionating column via silica gel trap which removes last traces of volatile hydrocarbons. Stripping in this column yields pure liquid oxygen in the bottom sump around the nitrogen condenser attached to the high pressure column.

The gas (air) from the hydrocarbon scrubber passes directly into the high pressure column where rectification yields pure nitrogen gas in the top, condenser section and oxygen-rich liquid air in the bottom sump. Liquid nitrogen, condensed by the liquid oxygen already produced, passes through an expansion valve to the top of the low pressure column for use in further stripping. The liquid air from the high pressure column joins that from the silica gel trap near its entrance to the low pressure column.

Liquid oxygen is drawn directly from the condenser sump, while pure nitrogen gas is taken from the top of the low pressure column through the heat exchangers to provide refrigeration. Waste nitrogen from the low pressure column is used for similar refrigeration.

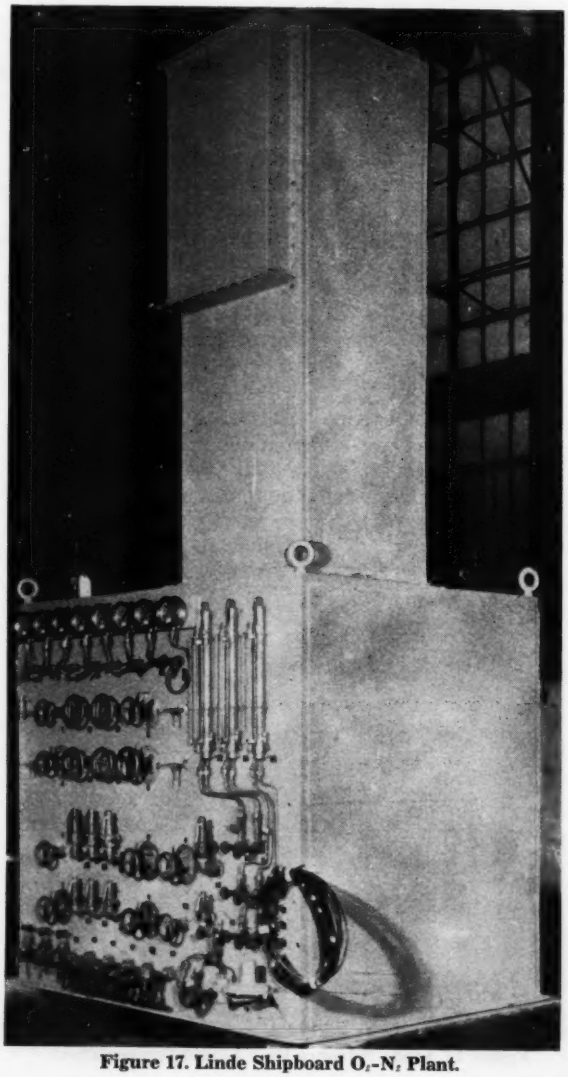

Figure 17. Linde Shipboard O_2-N_2 Plant.

This Linde plant is very compact with floor dimensions of 7′x7′ and overall height of only 12′. When supplied with 4460 CFH of air compressed to 3000 psi it produces 500 CFH of oxygen (as liquid) with 99.8% purity and 1550 CFH of 98% gaseous nitrogen. The principal problems in the prototype plant resulted from carry over of compressor lubricant. Oil "freeze up" shortened forecooler cycles as much as 50%. Some mechanical problems also occurred in the high speed air compressor.

Air Products Shipboard Plant

The Air Products shipboard plant pictured in Figure 18 and diagrammed in Figure 19 is the same in principle and general operating conditions as the Linde shipboard plant, but differs considerably in details. The 300 psi compressed air passes through a ring packed condensate trap and alternating silica gel dryers before entering the primary heat exchanger, air cooler and secondary heat exchanger. From here it passes through alternating fiberglass filters for removal of carbon dioxide ice and thence into the high pressure column. Oxygen-rich liquid air from the bottom of this column flows through a waste nitrogen refrigerated subcooler, a silica gel, hydrocarbon absorber and an oxygen refrigerated subcooler to the low pressure column. Pure liquid oxygen from the bottom of this column is pumped through the air subcooler and a strainer to the nitrogen condenser at the top of the high pressure column. Pure liquid nitrogen from the condenser flows to the top of the low pressure column to fractionate the liquid air. Liquid air is drawn from the condenser section and pure nitrogen gas is drawn from the top

Figure 18. Air Products Shipboard O_2-N_2 Plant.

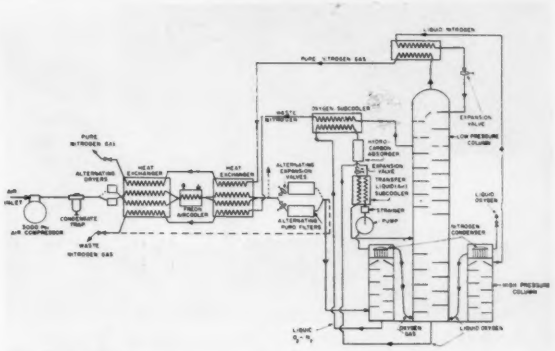

Figure 19. Flow Diagram of Air Products Shipboard O_2-N_2 Plant (1950).

of the low pressure column via the heat exchangers as in the Linde plant. Waste nitrogen from the low pressure column also passes through the heat exchangers and part of it is heated electrically to regenerate the alternating dryers and filters.

The major differences between this plant and the Linde plant are: use of primary dryers instead of a freeze out system; filtration of whole air, instead of liquid phase only; and concentric arrangement of high pressure and low pressure columns. The last arrangement was necessary because the multiplate columns of the Air Products plant could not be stacked without exceeding the 14′ shipboard height limitation. It requires transfer of liquid oxygen by pump rather than by gravity.

The principal operating problem of this prototype occurred in the refrigeration system and the high speed, 3000 psi air compressor. The plant is very compact, easy to operate, and efficient. It produces about 515 CFH of oxygen (as liquid) of 99.5% purity and 1500 CFH of 97% gaseous nitrogen when supplied with only 3700 CFH of air compressed to 2100 psig. Oxygen production can be increased to almost 600 CFH by increasing the air supply to 4000 CFH and the pressure to 2250 psig.

It is interesting to note that both the Air Products and the Linde shipboard plants will operate satisfactorily at 5° tilt, despite the fact that they have stationary columns. This immunity to tilting effects is achieved by improved bubble cap design. Incidentally, shipboard trials have shown that the importance of pitch and roll was somewhat overestimated in designing earlier plants.

AUXILIARIES FOR SHIPBOARD O_2-N_2 PLANTS

Successful production of oxygen and nitrogen aboard ship did not complete the story by any means. Safe, efficient use of the products requires suitable storage containers for liquefied gases, equipment for converting liquid to gas and charging it into cylinders, and arrangement for rapid overboard discharge of liquid reserves in case of emergency. The following principal auxiliaries grew up with the oxygen-nitrogen plant.

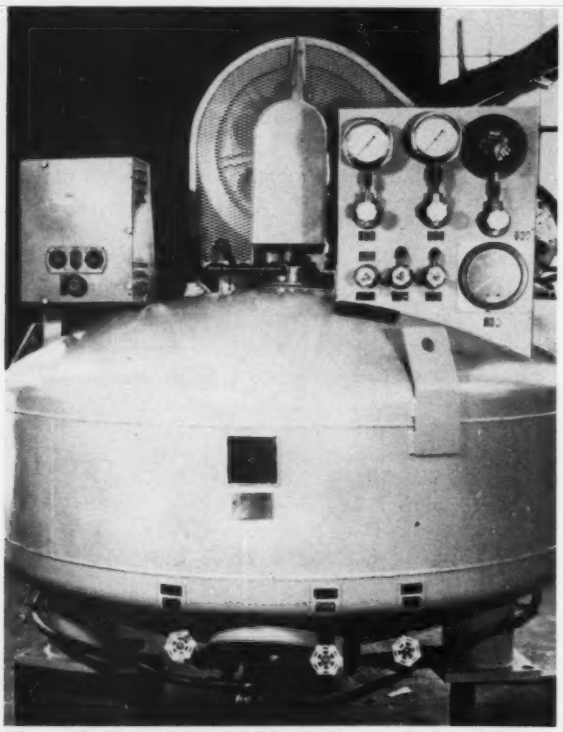

Figure 20. Linde Shipboard Liquid Oxygen Tank and Pump.

Storage Tanks

The first shipboard tanks for liquid oxygen were used on the USS *Vulcan,* USS *Antietam* and USS *Valley Forge* in conjunction with the Badger plant already described (1947). These were simple 150 gallon, double wall cylinders insulated with Santocel and vacuum. They contained liquid level try-cocks, pressure gages, control valves, vents and pressure-building coils for self-dumping. The last was simply an external coil of tubing connecting the liquid and vapor spaces of the tank in which liquid oxygen could be vaporized (pressurized) by ambient temperature to force out the liquid. These simple tanks performed satisfactorily and still are in use.

The second and most recent shipboard storage tank for liquid oxygen is shown in Figure 20. This 200 gallon tank is shaped like a partially flattened sphere and insulated with Santocel in an evacuated space between double metal walls. A reciprocating liquid oxygen transfer pump with carbon ring lubrication is submerged in the liquid of the tank to minimize vaporization during pumping. It is driven by a motor at the top of the tank. A vaporizing coil is situated outboard of the tank and heated with steam. The pressure building coil for self dumping is similar to that already described. This tank was developed by the Linde Company, and is used in all modern shipboard liquid oxygen plants.

The large spherical tank shown in Figure 21 was developed for advanced base use. It also is insulated with evacuated Santocel and equipped with a pressure building coil, but contains no liquid oxygen pump.

Figure 21. Advanced Base Liquid Oxygen Tank.

A smaller, air transportable, cylindrical tank also was used with certain Navy advance base oxygen plants.

Cylinder Charging Equipment

During development studies of the Navy liquid oxygen plant, a small hand pump with attached vaporizer was used for charging oxygen bottles. Since this was impracticable for service installation, the warm converter shown in Figure 22 was used for bottling the product of the original shipboard plants (Badger). This device consisted of a spherical tank surrounded by a discharge coil and immersed in a cylindrical hot water jacket. The bottle charging operation consisted of filling the sphere with liquid oxygen, connecting the discharge coil to a bank of four or five standard oxygen bottles and allowing the vaporized oxygen to establish the appropriate equilibrium pressure (1800 psi). The discharge coil then was switched to other banks of bottles (successively lower equilibrium pressures) until the sphere was essentially

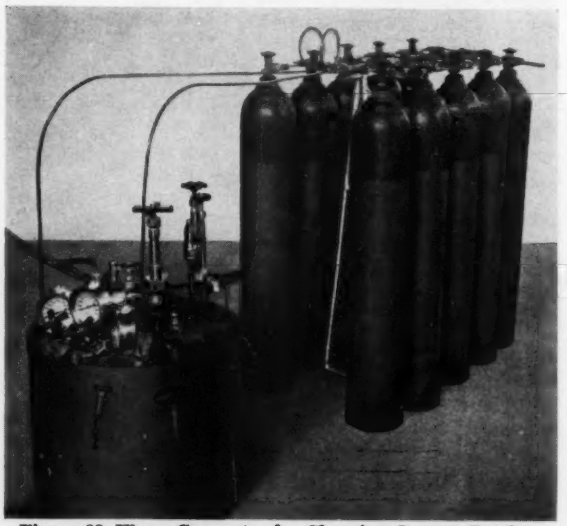

Figure 22. Warm Converter for Charging Oxygen Bottles.

empty. The partially filled bottles were topped off with subsequent fills of the sphere. The liquid oxygen pump and the external steam-heated vaporizer of the Linde tank assembly mentioned above have replaced this means of bottle charging in modern shipboard plants.

Figure 23 shows an early type, portable advanced base liquid oxygen pump and vaporizer which employed sea water as the vaporizing medium. The design vaporization rate of this unit could not be obtained except at tropical water temperatures but general performance was satisfactory.

The Engineering Experiment Station currently is evaluating several new prototype portable liquid oxygen pumps for advance base use.

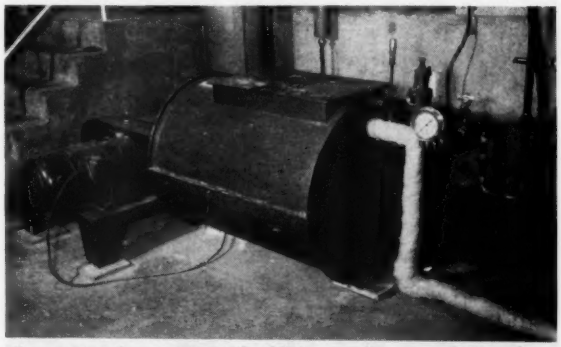

Figure 23. Advance Base Liquid Oxygen Pump and Vaporizer.

Air Compressors

Last, but far from least, of the auxiliaries is the air compressor. Shipboard O_2-N_2 plants use compact, high speed (1100 rpm) four stage, 3000 psi motor driven compressors with intercoolers and after coolers (sea water). Cylinder wear and valve fouling resulting from the high speeds and high temperatures have been very troublesome. Advance base compressors generally have lower speeds, lower discharge pressures and longer lives. Improved compressors now are being designed.

GAS HANDLING PROBLEMS

Effect of Liquid Oxygen on Decks

General acceptance of shipboard O_2-N_2 plants naturally raised questions regarding the effects of spilling and dumping in time of emergency. Oxygen is produced and stored as a pale blue liquid. Its extremely low temperature (—297.5°F) is known to embrittle many substances. Rubber becomes hard and friable like glass, and steel exposed to liquid oxygen will crumble under a hammer blow. Obviously, such a substance should not be allowed to contact ones body.

Station engineers explored the effects of accidental spillage by pouring liquid oxygen on a ¼ inch thick armor plate section of simulated ship's deck. The operation is shown in Figure 24. The result was almost immediate severe cracking of the steel as shown in Figure 25. The effectiveness of water flooding and various deck coverings in protecting steel from liquid oxygen also were determined. Figure 26

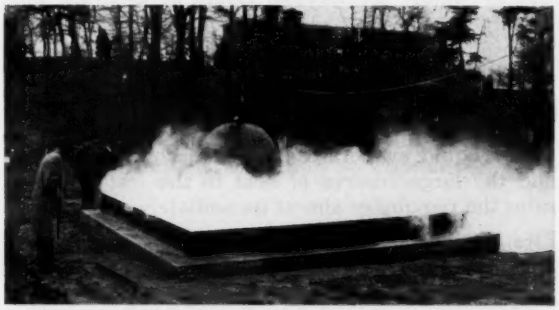

Figure 24. Testing Simulated Deck with Liquid Oxygen.

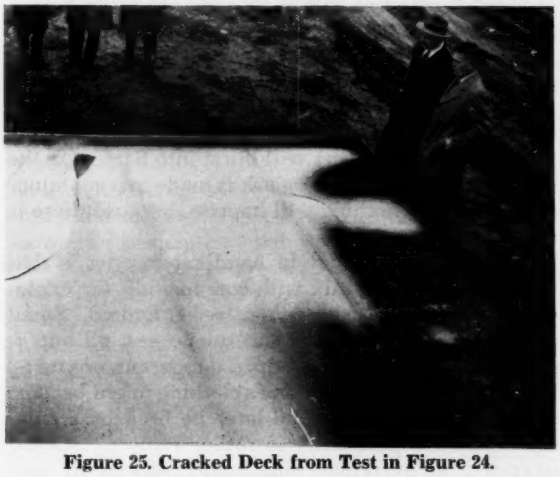

Figure 25. Cracked Deck from Test in Figure 24.

shows the insulating effects of several coverings. These experiments led to the conclusion that either insulation or water flooding will prevent cracking and that a base coat of concrete covered with aluminum is practicable and effective protection.

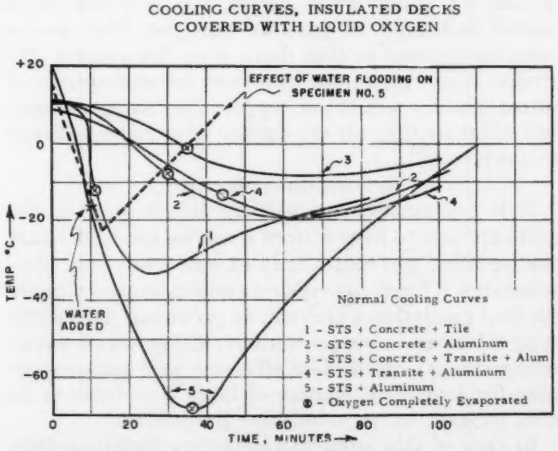

Figure 26. Effect of Water and Insulation on Deck Cracking.

Dumping Liquid Oxygen

Dumping tests conducted at this Station and aboard ship showed that no problems are involved in mixing liquid oxygen and water. If a large quantity of liquid oxygen is poured into a relatively small quan-

tity of water, the oxygen tends to separate into rapidly evaporating globules which partially coat themselves with shells of ice. If a relatively small quantity of liquid oxygen is emptied into a large quantity of water, it evaporates violently but harmlessly. In discharging liquid oxygen overboard, most of the liquid evaporates before reaching the water and the large reserve of heat in the water evaporates the remainder almost immediately on contact.

Fire Hazards

Many people have the false impression that oxygen is explosive, or at least combustible. This definitely is not the case. Oxygen simply supports combustion of other substances just as air does. In other words, it makes other things burn by supplying the oxygen necessary for their oxidation and the higher the oxygen concentration, the faster the burning after the kindling temperature is reached. If a glowing splinter of wood is thrust into a container of oxygen gas, the wood (not the oxygen) will burst into flame. On the other hand, if an electric spark is made in a container of oxygen gas, nothing will happen, because there is nothing to burn.

The principal danger in handling oxygen is that it may accidentally mix with combustible (or explosive) matter and subsequently be ignited. Small amounts of hydrogen gas, acetylene gas, oil vapor, gasoline or dust could produce dangerous mixtures, but they do with air also. One's clothing might become saturated with oxygen and later be fired by a cigarette, but this possibility is rather remote. Storing oxygen as an extremely cold liquid reduces the hazard considerably by increasing the quantity of heat necessary to attain the kindling temperature of any combustible matter.

Problems of Handling Liquid Nitrogen

Nitrogen can be produced as extremely cold (—320°F) water white liquid, but it generally is stored and used as gaseous nitrogen. This gas is completely inert so that there is no fire hazard. Nitrogen is not poisonous, however an atmosphere of nitrogen alone would not support life. Since nitrogen gas is lighter than air the danger of nitrogen suffocation is remote.

OXYGEN CONSERVATION

It is one problem to prepare liquid oxygen and quite another to keep it until it can be used. Because the liquefied gas exists only at extremely low temperatures, it tends to evaporate and disappear despite the best insulation which can be provided. While this type of leakage is not particularly dangerous it markedly reduces overall plant efficiency and opposes any plan for long term storage of large quantities of liquid oxygen, as for submarine propulsion.

In view of this problem a prototype helium refrigerator was built for conserving liquid oxygen supplies. A picture of it is shown in Figure 27. Compressed helium is cooled in an expansion engine loaded with an oil pump. The work done on the oil is dissipated as heat in the atmosphere and a small sea-water heat exchanger. The cool helium gas cycles through a heat exchanger on the compressed helium intake and eventually is reduced in temperature below the point of oxygen liquefaction. Coils carrying cold helium can be immersed in either the liquid or the vapor of a liquid oxygen tank to reduce evaporation losses. The plant pictured can save at least as much liquid as an oxygen generator of equivalent size can make and it needs no air supply. The plant functioned very well in prototype tests except for incidental mechanical problems in the expansion engine. Due to changes in program, the Navy has no immediate need for this conservation system. The future may tell a different story.

EXHALATION OF THE FLEET

It is not strange that most of the Navy's research has been directed toward the inhalation phase of oxygen generation rather than the exhalation phase of carbon dioxide removal and general air purification. Disposal of exhaled air has never been a significant problem with Navy air men or personnel of surface crafts. Until the past decade, even submarine crews considered carbon dioxide disposal an emergency problem to be handled with solid absorbents rather than a continuous purification problem. The atomic powered submarine with its freedom from battery charging and refueling stops and consequent prospect of long submersion changed this picture. The Navy began to think in terms of processes rather than non-regenerative absorbents for air purification.

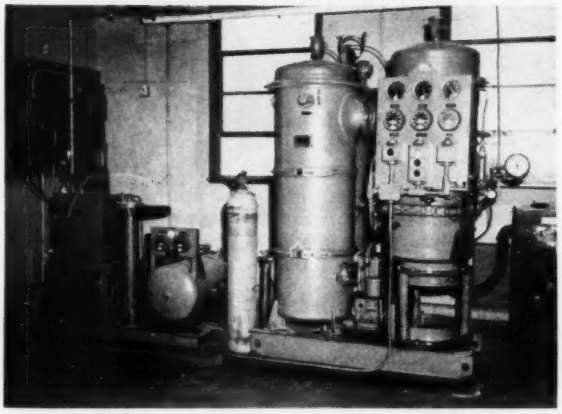

Figure 27. Helium Refrigerator for Conserving Oxygen.

Carbon Dioxide Absorption Plant

Development of this equipment started with a University of Pennsylvania contract in 1945. This yielded a purification cycle based on absorption of carbon dioxide by cold diethanolamine and periodic regeneration by counter current, vapor scrubbing in a hot, packed column. Modified equipment based on this plan was subjected to service tests aboard a submarine by Mare Island Naval Shipyard. This proved that atmospheres easily could be maintained at 2% CO_2 or less in normal living quarters and that personnel suffered no serious effects from short periods (several days) of such exposure.

Following these trials, the Girdler Corporation of Louisville, Kentucky designed and built a submarine prototype using essentially the same cycle. This employed a mixture of diethanolamine and diethyleneglycolamine which has somewhat better efficiency in reducing CO_2 to low residuals. This plant included an acid scrubber to minimize carryover of irritating amine vapors. It was installed on the USS *Nautilus* (SSN571) and performed approximately as expected. Since the plant requires only power, which is continuously available on a nuclear vessel, it is readily adaptable to longterm submergence. Operating problems, such as corrosion, mechanical failures, and effluent contamination will determine its practicability. Figure 28 shows a typical view of the Girdler prototype.

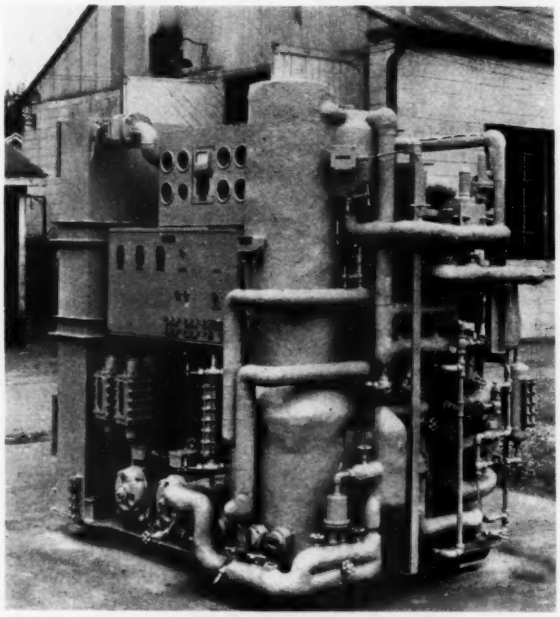

Figure 28. Girdler CO_2 Absorption Plant.

Non-Regenerative CO_2 Adsorbents

Development of the CO_2 plant has not eliminated the need for one shot CO_2 adsorbents. Soda lime, the traditional CO_2 absorber for short submergence periods, still is the principal general purpose air purifier for submarines because of its ready supply and relatively low cost. In recent years it has been supplemented with a more powerful chemical, lithium hydroxide. This highly caustic material is best carried as pellets in cannisters equipped with circulating fans. Pelletizing markedly reduces the probability of entraining irritating caustic in the air discharged from the cannisters.

WATCH YOUR BREATH—THE TESTING PROGRAM

These relatively new gas generating plants and the prospect of markedly extended underwater operations have magnified the importance of shipboard gas testing equipment in the Fleet. Rugged, accurate analyzers are needed for measuring purity of inerting nitrogen and breathing oxygen produced by the liquid air plants. Indicators or recorders for oxygen, carbon dioxide, water vapor, carbon monoxide and hydrocarbons in submarine atmospheres also may be required. Equipment and methods once peculiar to the analytical laboratory are being reduced to dimensions and characteristics appropriate for shipboard service.

Oxygen Meters

Most automatic analyzers for gaseous oxygen are based on the very convenient fact that oxygen is more strongly paramagnetic than other gases. This means that a gas stream will be drawn into a magnetic field in proportion to its oxygen content. In the Pauling oxygen meter, a dumbbell consisting of two tiny glass balls connected with a thin glass rod is suspended on a hairlike quartz thread in an unbalanced magnetic field. When a mixture of oxygen and other gases is passed by this field, attraction of oxygen into the field turns the dumbbell and a tiny mirror attached to the quartz thread reflects a light beam on a scale calibrated in per cent oxygen. Figure 29 shows the principle of the meter.

In the Hayes oxygen meter used with modern shipboard oxygen-nitrogen plants, oxygen is pulled over a heated wire by the magnetic field and the extent of cooling thus achieved is compared with a reference wire using a Wheatstone bridge.

Moisture Meters

The moisture content of breathing oxygen is important because of possible freeze-ups in high altitude travel. While considerable work has been done with moisture sensitive color indicators and conductometric methods, dew-point meters still are the most reliable measure of extremely low humidities.

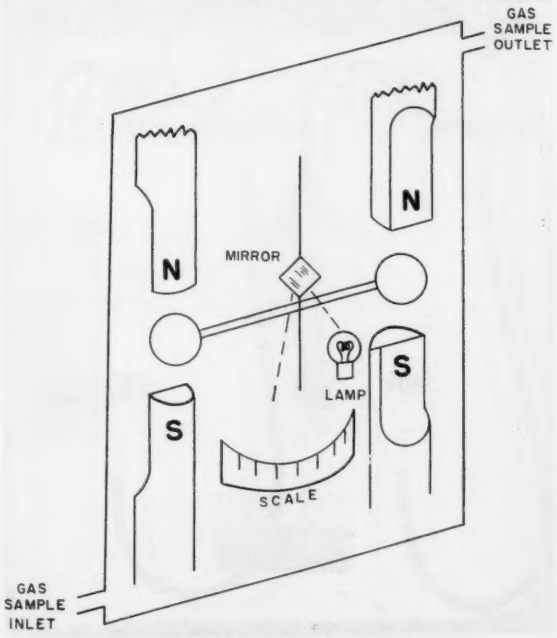

Figure 29. Principle of Pauling Oxygen Meter.

The basic principle of such a meter involves cooling a mirror-surfaced metal and noting the exact temperature at which dew condenses on it from the test gas. Cooling generally is accomplished by admitting carbon dioxide at reduced pressure to one side of the mirror and determining the mirror temperature at the point of condensation from the vapor pressure data of the carbon dioxide. Actually there is little need for dew-point measurements in oxygen gas made from liquid air, since freeze out eliminates moisture.

Orsat Equipment

The traditional Orsat apparatus still is used for referee determinations of oxygen as well as for measurement of carbon dioxide and carbon monoxide. The principle is the same in every case, namely, admitting a measured volume of gas to an absorptive solution and noting the gas volume reduction. Oxygen-rich mixtures generally are absorbed in cupra-ammonium or pyrogallate solutions. Caustic is used for CO_2 and cuprous solution is used for carbon monoxide. A typical Orsat apparatus is shown in Figure 30.

Acetylene Test Kit

The possibility of contaminating the compressed air supply with acetylene from welding operations or decomposition of air compressor lubricants and the potential explosiveness of acetylene-oxygen mixtures necessitated a special kit for determining small quantities of acetylene in liquid oxygen. A kit developed at EES is shown in Figure 31. The test is based on the fact that ammoniacal cuprous chloride and acetylene react to form a pink color. The test

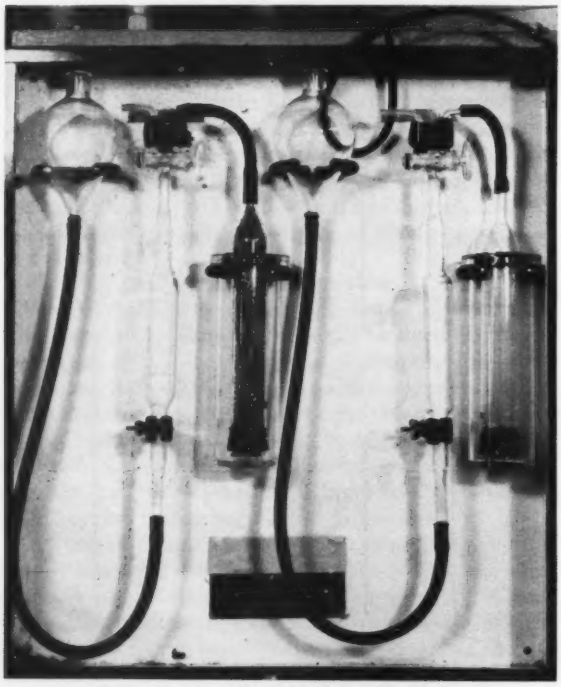

Figure 30. Orsat Gas Analysis Apparatus.

Figure 31. Test Kit for Acetylene in Liquid Oxygen.

is applied by evaporating a sample of liquid oxygen to near dryness in a test tube, adding the reagent and comparing the color with a color standard. The test is senstive to 1 ppm or more of acetylene.

Miscellaneous Test Equipment

Since gage glasses cannot be used on low temperature liquids, the levels in oxygen tanks are indicated by dial type meters geared to metal bellows of the aneroid barometer type. One side of the bellows is exposed to the vapor of the vented tank while the other side is exposed to the hydraulic head of the liquid therein. The dial is calibrated to show the liquid depth corresponding to the differential pressure.

The low temperature thermometer used on liquid air plants consists of a gas filled bulb attached by a capillary to a Bourdon type gas pressure indicating device. Thermocouples are used to calibrate the thermometers.

In addition to these relatively common testing devices, a variety of specific instruments may be used for special tests. For example, a special kit developed by the Bureau of Standards and marketed by Mine Safety Appliance Co. is used for measuring extremely low concentrations of atmospheric carbon monoxide. The test consists of pumping a known amount of atmosphere through a glass tube of chemical by means of a calibrated squeeze bulb and comparing the color developed with a series of standard colors.

WHAT DOES THE FUTURE PROMISE?

When one reviews the giant strides of the Naval Gas Program during the past decade it is easy to expect almost anything to happen in the future. At the pres-

ent time, the needs of the surface fleet (carriers and tenders) appear to be well taken care of so that the emphasis probably will be on providing better atmospheres for the atomic submarine. The possibility of generating oxygen from sea water by electrolysis already is being considered and undoubtedly will receive much attention in years to come. Someone has even suggested the possibility of separating dissolved air from sea water to sustain submarine crews—after all, fish can do this. To the conservative scientist this certainly seems like a dream, if not a nightmare. On the other hand, atomic power itself shared the same reputation just a few years ago.

The problem of reconditioning stale air is less acute than that of providing oxygen from a source other than the atmosphere, but work needs to be done nevertheless. Experiments have been made with a foaming amine absorber which promises to be much more efficient than the liquid amine cycle now in use. Attempts undoubtedly will be made to develop other regenerative chemical adsorbers with less objectionable effluent than that of the amine scrubbers. If this is not the case, one might expect better after scrubbers to appear. Better humidity control and deodorizing systems probably will develop along with the atomic submarine.

If generation of oxygen from water should prove to be impossible or impracticable, or if appreciable quantities of nitrogen should be necessary for inerting submarine systems, emphasis might shift back to a compact shipboard oxygen-nitrogen plant operating in conjunction with improved storage facilities for large quantities of gaseous or liquid products. On the other hand, the present system of filling large, high pressure bottles from shore based plants may prove more practicable.

It would not be surprising to find great changes in future gas testing equipment, particularly on the submarines. Efforts now are being made to adapt such laboratory instruments as the infrared spectrometer and the mass spectrograph to semi-automatic testing of the several important gases in the respiration cycle.

CONCLUSION

The amazing gas program outlined above has strengthened the Fleet for new and exacting obligations. This has not occurred by chance. Carefully planned research programs, typical American industrial ingenuity and the inspiration of necessity have fertilized the program as in so many other fields well known to Naval personnel. The present stature of Naval gas facilities is a great tribute to the foresighted men who planned the program in the early years of the last war. The breath of the fleet is very adequate today and undoubtedly will improve with the years to come.

One of the Navy's newest type ships can load and unload all types of land vehicles, including heavy tanks. Designed for use in the Arctic, it will be especially valuable where there are only limited port facilities.

* * *

Called the "Floating Ice Box," the USS RIGEL (AF-58) is a new kind of Navy ship, built specifically for carrying refrigerated cargo. With 351,000 cubic feet of storage space, she has more room than in 35,000 home-type refrigerators.

TRANSACTIONS OF THE
INSTITUTE OF MARINE ENGINEERS

CRANKCASE EXPLOSIONS IN MARINE ENGINES

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Crankcase explosions occur very rarely considering the number of engines in use. A few times a year, however, an incident of this kind occurs with results that are usually not serious, but occasionally disastrous. In 1947 a marine crankcase explosion resulted in the loss of twenty-eight lives. In view of the importance of the subject the British Shipbuilding Research Association put in hand a comprehensive investigation under the authors' direction, at Imperial College. Work began in December 1948 but the investigation developed a number of aspects, some of which are still being pursued.

The available evidence suggests that in crankcase explosions, the explosive medium is normally formed from lubricating oil and air. The general temperature in the crankcase is not high enough to give rise to any significant pressure of oil vapor, but a suspension of liquid droplets may form either by mechanical dispersion of the oil as spray, or by its volatilization in contact with a relatively hot engine part followed by condensation as a mist. The volatility of the lubricant may, of course, be increased by fuel oil dilution, but so far there has been no indication that this is an essential factor in crankcase explosions, which have, indeed, occurred in steam engines.

Mechanical spray is present in a crankcase during normal running. Some condensed mist may be expected because the lubricated parts tend to be at a temperature above the average for the crankcase. These normal temperature differences, however, are not sufficient to give rise to rapid mist formation and the ordinary breathing of the crankcase usually maintains the mist concentration at a very low level. On the other hand, in the event of serious overheating of a part to which oil has access, condensed mist formation is accelerated and will proceed rapidly so long as overheating of the part and the access of oil to it continue. Condensed mist is usually referred to by engineers as "smoke" and is a recognized sign of overheating. Its formation may be accompanied by cracking and oxidation of the oil to form gases and vapors which are even more hazardous than the mist itself. At the same time, the overheated part constitutes a potential source of ignition and thus the essential elements for an explosion are present together.

The evidence indicates that the majority of crankcase explosions do in fact originate in this way, arising initially from mechanical overheating. For this reason, in planning the investigation, attention was directed first to the formation and explosive properties of condensed lubricating oil mist.

THE OIL MIST HAZARD

A METHOD was developed for the controlled generation of oil mists in air with a view to determining the lower limit of inflammability, i.e. the least oil/air ratio for the continued propagation of flame on ignition[1]. The principle of the method was that a controlled feed of oil was evaporated completely at 430-440 deg. C. in a stream of nitrogen which then impinged on a stream of cooled oxygen-enriched air. A suspension of oil droplets was thereupon formed by condensation. The ratio of oxygen to nitrogen in the supporting gas was adjusted, through the relative flow rates, to be as in air.

The mist thus formed was passed down a vertical 2½-in. diameter glass tube of length about 5 feet and that issuing from the lower end was extracted to

waste through an oil filter. Back currents of air up the tube, which disturb conditions near the lower end, were avoided by fitting a brass cup around the bottom of the tube.

To test a given mixture for inflammability, the cup was removed from the bottom of the tube and a ¾-in. high spirit-lamp flame was applied. If the mixture ignited and flame propagated to the top of the tube, the mixture was judged to be inflammable, but not otherwise. By varying the rate of oil feed to the evaporator, the proportion of oil in the mist was adjusted until it was the minimum for complete flame propagation. Before further altering any settings the mixture actually reaching the bottom of the tube was sampled on a microscopic slide for droplet size analysis and a measurement made of the oil/air ratio by filtration of a measured volume of suspension through a tared filter.

Analysis of the air leaving the bottom of the tube, following removal of the oil droplets by filtration, failed to reveal any combustible matter. From this it was concluded that under the conditions of mist generation employed the oil was not suffering appreciable cracking.

The mist produced contained, of course, a range of droplet sizes. To a limited extent the size distribution could be influenced by changing the separation distance between the cold and hot jets in the generator. The bulk of the weight of oil tended to be concentrated in the range 5-10 microns (0.005-0.010 mm.) diameter, but by variations in the jet separation droplets down to about 2 and up to about 20 microns could be brought into relative prominence.

Using Shell Lubricating Oil, Talpa 30, it was found that the mean lower explosive limit of the mist was 0.049 oz. per cu. ft. and that this figure was not affected by such changes as could be made in the droplet size distribution. This figure is in close agreement with the lower limits in air for pure hydrocarbon vapors of various types, some of which are shown, in the same units, in Table I. This immediately suggests two generalizations: —

(1) that the lower limit of a condensed mist is the same as it would be if the liquid fuel could exist as vapor at the ambient temperature;
(2) that the lower limit of a condensed hydrocarbon oil mist is not very dependent upon the precise constitution of the oil.

TABLE I—LOWER LIMITS OF INFLAMMABILITY OF HYDROCARBON VAPORS IN AIR

Hydrocarbon	Lower limit (oz/cu. ft. ± 0.004)
Pentane	0.049
Hexane (normal and iso)	0.047
Heptane (normal and iso)	0.050
Octane	0.051
Decane	0.047
Cyclohexane	0.049
Benzene	0.049
Amylene	0.048
Butadiene	0.049

It was therefore tentatively concluded that other hydrocrabon oil mists would be likely to give a very similar figure.

By a slight variation in the experimental arrangements, a controlled supply of carbon dioxide was fed into the mist under test and the effect of various additions of this diluent upon the lower explosive limit was examined. It was found that when the percentage by volume of carbon dioxide in the mixture: air+ carbon dioxide: was 28.0 inflammable mists could be formed over a narrow range of oil concentration; but when the percentage was 28.3 no inflammable mixtures could be formed at all.

TABLE II—EXTINGUISHING CONCENTRATIONS OF CARBON DIOXIDE AND NITROGEN IN AIR FOR HYDROCARBON VAPORS

Hydrocarbon	Extinguishing concentration (vol. per cent)	
	Carbon dioxide	Nitrogen
Propane	30	43
Butane (normal)	28	41
Butane (iso -)	27	41
Pentane (normal)	29	43
Hexane (normal)	29	42
Benzene	32	45
Propylene	30	43

Table II shows corresponding extinguishing concentrations of carbon dioxide and nitrogen (see later) for various pure hydrocarbons. Again the figures are similar to one another and to that obtained for the oil mist and it is indicated that the two generalizations regarding the lower limit, stated above, may be extended to the extinction limit for carbon dioxide and other diluents.

A point that rapidly became apparent in the course of the measurements of explosive limits was that the optical density of a condensed oil mist of lower limit concentration (i.e. about 0.049 oz. per cu. ft.) is very high. The light from a 25-watt electric lamp is totally obscured by a layer only a few inches thick. This shows not only that explosive concentrations of oil mist would be very obvious on inspection, but also that it would be comparatively easy to arrange an automatic detecting device that would operate, for example, through the interruption of a beam of light falling upon a photoelectric cell. Instruments of this kind are already in use for the detection and measurements of smoke in boiler flues and for other purposes.

With this possible development in mind, and also to obtain information on any hazard arising from oil mist during normal running, observations were made on Doxford engines both on the test bed and in ships at sea. Oil mist concentrations arising in the crankcases were measured by withdrawing metered volumes of crankcase atmosphere through tared filters and weighing the oil collected. The coarser mechanical spray was excluded from the filter by suitable baffles.

The test-bed observations were of a preliminary nature and were made on a standard 5-cylinder opposed-piston Doxford engine, 670 mm. bore × 2,320

mm. combined stroke, with center scavenge pump situated between numbers 3 and 4 cylinders. The engine was run, with some stops, for about ten hours at a steady speed of 108-110 r.p.m.

Under conditions of strong illumination, a faint oil haze became visible after fifteen minutes' running, but the concentration of oil mist never became sufficient to measure satisfactorily. There was some indication, however, that the concentration was slowly increasing throughout the test.

The observations were therefore continued over an extended period in similar engines in ships at sea. The first test of this kind took place on the 5-day run from Liverpool to Las Palmas in December 1951, and the second test on the return run on a sister ship in January 1952.

It was found that the increase in oil mist concentration did not continue after the first twenty-four hours' running and no concentration of mist greater than one hundredth of that at the lower explosive limit was observed at any time.

Both in the bench test and in the tests at sea the samples of crankcase atmosphere were subjected to gas analysis following the removal of oil mist by filtration. No inflammable constituents were detected, but it was found in the tests at sea that small percentages of carbon dioxide appeared in the atmosphere, especially later in the run, accompanied by corresponding deficits of oxygen. The highest percentage of carbon dioxide found was 2.4. This is insufficient to have any significant effect on the oil mist explosion risk should concentrations of oil mist of the magnitude already indicated arise in the crankcase atmosphere.

The equivalence of carbon dioxide formed and oxygen disappeared suggests that this change in composition of the crankcase atmosphere was due to the gradual accumulation of cylinder blowby gases rather than to lubricating oil oxidation. The absence of inflammable constituents indicates that oil cracking was inappreciable and that any small blowby of fuel was taken up by the lubricant oil.

THE OIL SPRAY HAZARD

During the tests on running engines mentioned in the last section, some observations were made with regard to the mechanically formed oil spray. Quantitative measurements were unsuccessful, but it became clear that after the initial period of running a fair concentration of fine mechanical spray was set up in the crankcase but that the drop size was very markedly larger than that prevailing in a condensed mist. No exact information existed on the inflammability of liquid sprays and a special investigation was therefore undertaken[2, 3].

After experimental development extending over a considerable period, it has been possible, using pure liquids of high boiling point as fuels, to prepare inflammable suspensions of liquid droplets in air in which the droplets are of controllable and substantially uniform size. The method depends upon the controlled condensation of the vapor of the fuels and is a development of a method used by Professor V. K. La Mer, of Columbia University, for the generation of dilute monodisperse aerosols.

By this means the lower explosive limit of suspensions tetrahydronaphthalene (tetralin) in air has been measured as a function of the droplet size up to 130 microns (0.13 mm.). By using liquids of even higher boiler-point, e.g. cetane, the measurements can be extended to suspensions of at least 300-micron drops.

With these larger drops, the conception of fuel/air concentration requires some discussion. Normally this may be taken to be equal to the weight of fuel contained in a given volume of air, divided by the volume of air. In a suspension of droplets, however, the droplets are not stationary with respect to the air, but move relative to it at a rate which increases as their size increases. A given weight of droplets is therefore only instantaneously associated with a given volume of air and thus the normal conception of concentration, which may now be described as the instantaneous concentration, has only limited relevance.

In the case with which we are concerned—that of a flame passing through a droplet-air mixture—the true concentration of fuel is given by the ratio of the weight of fuel passing into the flame in any given period of time, to the volume of air entering the flame simultaneously. For any given value of the "instantaneous concentration," the true concentration entering the flame is greatest when the flame is traveling in the opposite direction to the fuel droplets. The passage of flame up a tube down which the droplet-air mixture is passing fulfils this condition and it is in general true, since droplets tend to fall vertically, that flame traveling vertically upward will encounter the maximum ratio of fuel to air in any given system. Thus, a lower limit of inflammability measured under the conditions should have the minimum value.

Lower limits for tetralin-air suspensions for the passage of flame up a 2½-in. tube have so far been measured up to a drop size of 130 microns. The instantaneous concentration at the lower limit measured directly, falls smoothly from 0.046 oz. per cu. ft. for drops of 10 microns or less, to 0.003 oz. per cu. ft. at 130 microns. True concentrations entering the flame front at the lower limit have been calculated approximately from the "instantaneous" figures. There is some indication that the true concentration remains independent of the drop size at about 0.046 oz. per cut. ft., although more accurate data regarding relative velocities of drops, air and flame are necessary to verify this conclusion. The investigation is proceeding.

Measurements of extinguishing concentration of nitrogen, as influenced by the drop size of the tetralin, have also been made. For drop sizes of 10 microns or less, the figure is 40 vol. per cent, which corresponds with typical figures for hydrocarbon vapors (see Table II). For larger drops, however, the figure has been found to rise, reaching 47 vol. per cent at 19 microns and 71 per cent at 45 microns. This result is sufficiently important, and at the same time unexpected, to require confirmation, and this is in hand.

If it is confirmed that the true concentration of fuel drops, relative to the air, entering the flame at the lower limit, is independent of drop size, and hence approximately equal to typical hydrocarbon vapor lower limits, then the properties of mists and sprays will conform in this respect to a very simple basic pattern. The assessment, in the same connection, of conditions in a crankcase will also become fairly simple, for the measurement of drop size distribution will be unnecessary, and all that will be required will be a measurement of the ratio: weight of oil volume of air across a plane at right angles to the direction of movement of the oil in any particular locality. This possibility is being pursued.

IGNITION OF MISTS AND SPRAY

The typical lubricating oil used in much of the present work is completely vaporized at about 400 deg. C. and its minimum spontaneous ignition temperature in air is below this figure. It follows that, in the most favorable circumstances (size and geometrical configuration of surface, optimum oil concentration, formation of aldehydes, etc., by slow oxidation) a hot surface at, or even below this temperature can ignite the oil. If the circumstances are such that ignition occurs readily, then oil coming in contact with the surface will burn before there is much formation of vapor or mist. The result will be fire (local at first) unless the crankcase atmosphere is explosive due to the presence of spray. If, however, circumstances are otherwise, extensive vapor, and hence mist formation may occur before ignition takes place and a mist explosion may ensue. If at any time the overheated surface begins to give off friction sparks, ignition of the vapor and mist may be precipitated.

The exact circumstances in which ignition is delayed beyond the temperature for rapid mist formation are under investigation at the present time. It does seem, however, that a relatively slow rise of temperature of an overheated part in a crankcase would tend to favor delayed ignition and hence the occurrence of explosion. Moreover, the slower the heating the greater the mist formation before ignition and hence, up to a point, the more violent the ensuing explosion, or the greater the likelihood of secondary explosion. In the same way it seems that a relatively copious supply of oil to the overheating part, due to mechanical spray or otherwise, would tend to delay ignition, with similar results.

EXPLOSION RELIEF

It is possible in principle to control the destructive effect of a crankcase explosion upon the crankcase itself by providing certain areas of relief through which the explosion products can be quickly released. The principle has been utilized to some extent through the provision of crankcases with explosion valves and bursting diaphragms. However, the technical literature gives scanty information regarding the effectiveness of such devices and a further investigation was therefore undertaken.

A marine boiler shell of some 200 cu. ft. capacity was procured to serve as an explosion chamber. The vessel was about 12ft. 6in. long and 4ft. 2in. diameter and was tested hydraulically to a pressure of 350lb. per sq. in. It was set up with its major axis horizontal and for the earlier part of the work about two-thirds of the length was filled with compressed sandbags and walled off, leaving an approximately equidimensional chamber at one end of capacity 60.6 cu. ft. Later the full capacity of the vessel was employed.

Flanges were fitted, three equally spaced along the side and one at the end of the 200 cu. ft. chamber, on to which blank plates, orifice plates or relief valves of various kinds could be bolted as required. There were also an ignition source, filling and purging connections, an internal fan and an attachment to a recording manometer. Facilities were provided for recording the time of appearance of flame at open vents and the progressive movements of relief valves. In the earlier stages of the work optical recording manometers of two types were employed, but later the Safety in Mines Research Establishment piezo-electric oscillograph recording manometer[4] was used exclusively.

The practical object of the work was, of course, to provide data relating to the explosion of lubricating oil mists as they arise in engine crankcases. It was realized at the outset, however, that the controlled generation of oil mists on the necessary scale would be a matter of some difficulty and this was confirmed by experience. In order, therefore, to expedite the investigation, systematic work, involving large numbers of tests, was done using pentane vapor as the inflammable constituent. Experiments with oil mist were limited to those needed to link the behavior of this material with that of pentane.

The justification for the use of pentane vapor as a substitute for oil mist lies in the similiarity of the explosion properties of the latter with hydrocarbons generally. Some aspects of this similarity have been touched upon already. Further evidence was forthcoming from a determination of the fundamental flame-speed of lubricating oil mist as a function of the oil concentration[1]. The magnitude and variation of this quantity were found to be very similar to those for a hydrocarbon such as pentane. Similar explosion behavior was, therefore, expected.

A series of pentane-air explosions were first carried out in the 60.6 cu. ft. chamber, without vents, to ascertain the effect of varying the fuel/air ratio. The results are summarized in Table III. The theoretical pentane/air mixture for complete combustion con-

TABLE III—EXPLOSIONS OF PENTANE-AIR MIXTURES IN CLOSED VESSEL

Mixture pentane, per cent	Maximum pressure, lb. per sq. in.	Maximum rate of pressure rise, lb. per sq. in. per millisec
2.0	93	0.39
2.3	108	0.75
2.7	113	0.9
3.0	117	1.7
3.25	122	3.3
3.5	110	3.7
4.0	106	3.2
4.3	109	2.8

tains 2.56 per cent by volume of the fuel and the mixture for maximum fundamental flame speed contains 2.9-3.0 per cent. Below 2.5 per cent comparatively slow explosions were obtained, but above this figure the explosion changed in character, a slow initial pressure increase being followed by a very rapid rise accompanied by oscillations on the pressure record. The rate of pressure rise reached its peak with about 3.5 per cent of pentane.

To carry out similar experiments with oil mist, a safe and satisfactory form of mist generator had to be developed. A tube evaporator was first constructed but this was difficult to control and liable to give rise to spontaneous ignition of the mist produced. A thermal storage evaporator was therefore constructed, consisting of a stout steel vessel, about 1ft. in diameter, by 1ft. deep, containing 1 cwt. of ½-in. and ¾-in. steel balls, and provided with external electric heating. The requisite quantity of oil, of the order of a pint, was preheated to a temperature somewhat below its boiling range and injected through jets into the evaporator. Using Shell Lubricating Oil, Talpa 30, an explosive concentration of mist could be obtained with an evaporator temperature of 500 deg. C. or above, and so long as the pipe to the explosion chamber was fitted with a jet to promote rapid mixing with air, spontaneous ignition did not occur in the chamber.

The control of mist concentration in the explosion chamber was not good, however, since varying amounts of oil condensed out in the system, but it was found possible to check the concentration actually prevailing by sampling the mist just before firing. To show the variations observed both in mist concentration and in the characteristics of the explosion, the results of a number of tests are listed in Table IV, arranged in order of increasing quantity of oil passed into the explosion chamber, or increasing mist concentration in the explosion chamber, where known.

TABLE IV—EXPLOSIONS OF MISTS OF SHELL LUBRICATING OIL, TALPA 30

Amount of oil introduced, cc.	Evaporator temperature, deg. C.	Measured mist concentration, oz. per cu. ft.	Maximum pressure, lb. per sq. in.	Maximum rate of pressure rise, lb. per sq. in. per millisec
320	500	—	111	4.1
320	500	—	103	1.3
400	500	—	113	4.4
426	504	—	99	5.3
428	505	—	111	1.1
450	510	—	105	0.85
500	509	—	112	1.4
680	510	0.054	95	4.9
600	517	0.0715	100	4.4
700	506	—	99	1.4
1000	516	0.080	89	1.7
1000	517	0.128	87	1.4

Comparison of tables III and IV shows that the maximum explosion pressures obtainable in a closed vessel from pentane and from oil mist are very similar, those for the latter being slightly less on average. The rates of pressure rise in some of the oil mist tests, however, are definitely in excess of anything obtained with pentane. This is explained, in part at least, by the fact that mist generation was apt to be accompanied by the formation of cracked oil gases. Gas analyses of the mixtures containing 0.054 and 0.0715 oz. per cu. ft. of oil (see Table IV) indicated the presence of approaching 1 per cent of acetylene and possibly hydrogen as well. These gases have much higher fundamental flame speeds than the hydrocarbons and it is considered that their presence in the proportion indicated could account for the enhanced rates of explosion observed unaccompanied by increase in maximum pressure. No doubt the amount of cracking, like the mist concentration, was somewhat variable in these tests and this would account for the variations in observed rates of pressure rise.

The rate of explosion, as indicated by the rate of pressure rise in a closed vessel, is the principal factor determining the effectiveness of any explosion relief device. In view, therefore, of the variation in this quantity associated with the oil mists produced, it was preferable to continue the investigations of explosion relief using pentane vapor, which was capable of giving reasonably reproducible explosions.

First, the effect of varying circular relief area was investigated, using 2.7 per cent and 3.5 per cent pentane-air mixtures. In these experiments the openings were covered with waxed brown paper bursting at about 0.5lb. per sq. in. The maximum explosion pressures measured are shown in Table V.

TABLE V—EFFECT OF AREA OF PAPER-COVERED RELIEFS ON MAXIMUM EXPLOSION PRESSURE

Relief		Maximum explosion pressure, lb. per sq. in.	
Diameter, inches	Ratio, sq. in.per cu.ft.	2.7 per cent mixture	3.5 per cent mixture
None	—	113	110
6	0.47	73	97
12	1.87	43	56
18	4.20	22	32
24	7.46	4	—

The effect of the method of covering the relief area was then studied, ranging from a light card merely laid against the orifice to a spring-loaded plate valve opening at up to 4 lb. per sq. in. or multiple layers of cellophane. Two mixtures and two relief areas were used and the results are shown in Table VI.

With all closures of the bursting type, oscillatory pressure records were obtained except with very weak mixtures (less than 2.5 per cent). The onset of oscillation and rapid combustion was associated, however, with the bursting of the diaphragm. It seemed clear that the bursting was actually accelerating the explosion, perhaps through the generation of pressure waves. Thus, bursting closures tended to lead to higher maximum pressures than non-bursting closures covering the same relief areas, especially where, as with the 2.7 per cent mixture, the tendency to oscillatory explosion was not normally marked.

TABLE VI—EFFECT OF METHOD OF CLOSING RELIEF ON MAXIMUM EXPLOSION PRESSURE

Closure		Maximum explosion pressure, lb. per sq. in.			
		2.7 per cent mixture		3.5 per cent mixture	
Method	Bursting or opening pressure, lb. per sq. in.	12-in. relief	18-in. relief	12-in. relief	18-in. relief
Card (1)	Negligible	25	8	58	30
Card (2)	0.2	41	21	—	—
Paper	0.5	43	22	56	32
Cellophane slit before firing	0.5	—	14	—	—
Cellophane	2.4	—	29	—	—
Plate valve	4	—	23	—	33
Cellophane 3 layers	6.2	—	29	—	—

With the 3.5 per cent mixture the difference was not noticeable.

With the plate valve, the plate itself rose and fell, in some cases more than six times in the course of the explosion, and the pressure showed corresponding variations. For weak mixtures, the initial pressure rise was greatest and the maximum pressure was determined by the opening pressure of the valve. For rich mixtures the highest pressure was reached at the end of the explosion and was apparently determined by the area of the relief.

In a crankcase, the suspension of oil drops is stirred by the moving parts. The effect of this on pentane-air explosions was examined by running the four-bladed mixing fan during firing. The fan motor ran at a fixed speed of 1,420 r.p.m. but a varied stirring effect was obtained by using fans of different diameters.

In closed vessel explosions, stirring accelerated the rate of pressure rise without substantially increasing the maximum pressure. Thus with the 2.7 per cent mixture (c.f. Table IV) the maximum rate of pressure rise was, for a 12-in. fan 2.1, for a 17.5-in. fan 3.95, and for a 24-in fan 5.75lb. per sq. in. per millisec. With the richer mixtures, however, stirring suppressed the vibratory tendency in the pressure record. In vented explosions, too, oscillations were suppressed and for this reason the use of the smaller fans with the larger relief areas actually reduced the maximum explosion pressure, as is shown in the summary of results given in Table VII.

TABLE VII—MAXIMUM EXPLOSION PRESSURES (LB. PER SQ. IN.) FOR 2.7 PER CENT PENTANE-AIR MIXTURE WITH VARIOUS RELIEF AREAS (PAPER-COVERED) AND STIRRED WITH FANS (1,420 R.P.M.) OF VARIOUS DIAMETERS

Vent size		No fan	Fan diameter, in.		
Diameter, in.	Ratio, sq. in. per cu. ft.		12	17.5	24
6	0.47	73	80	—	—
12	1.87	43	46	47	65
18	4.20	22	9	18	33
24	7.46	4	—	—	12

Theoretical consideration indicates that the ratio of relief area to chamber volume, necessary to limit the maximum pressure due to a given explosion to a fixed figure, should decrease with increasing chamber volume. For the idealized case of a sphere with central ignition and uniformly distributed relief, the relief area works out to be proportional to the surface area (square of the diameter) for a given maximum pressure.

In order to get some indication of the practical scale effect, explosions were carried out in the full 200 cu. ft. of the explosion vessel instead of the 60 cu. ft. at first used.

In the closed vessel the maximum explosion pressure was unaffected by the increase in scale but the richer mixtures no longer gave the rapid vibratory explosions. The maximum rates of pressure rise for the 3.0 per cent and 3.5 per cent mixtures were reduced (c.f. Table III) to 0.8 and 1.26lb. per sq. in. per millisec respectively.

Results obtained with various relief areas merely covered by a light card are summarized in Table VIII. In none of these experiments were rapid vibratory explosions obtained and the lower explosion pressures obtained were due to this to some extent at least. In view of this it is not clear whether there is a scale effect on relief requirements of the type envisaged theoretically, although there is some indication that this is so. The position of the source of ignition relative to the relief area is also important, however, and in the more effective arrangement they are close together.

TABLE VIII—EFFECT OF LIGHTLY-COVERED EXPLOSION RELIEF AREAS IN 200 CU. FT. CHAMBER

Reliefs				Mixture per cent pentane	Maximum explosion pressure, lb. per sq. in.
Number	Position	Diameter, inches	Ratio, sq. in. per cu. ft.		
1	Mid-side	18	1.3	3.25	22
1	Mid-side	18	1.3	3.75	35
1	End (ignition near)	24	2.25	3.5	4
1	End (ignition remote)	24	2.25	3.5	16.5
3	Alongside	18	3.8	3.5	2.5—3
3	Alongside	18	3.8	4.0	1.5—4

The work on explosion relief clearly illustrated the complexity of this subject, and indicated that it is not possible to get data from an explosion chamber that can be applied directly to an actual crankcase. This is because several unpredictable factors may intervene, and of these the incidence of rapid vibratory explosions, the cracking of oil mist and the action of stirring tend to make relief more difficult. Any kind of closure over the relief area is liable also to retard relief, but especially bursting diaphragms, because they may actually accelerate the explosion. It is also known, although experiments were not done on these aspects, that the explosion is accelerated and relief

rendered less effective by an extended source of ignition and the passage of explosion between inter-communicating chambers. Against all this we see only two favorable tendencies: with increasing chamber size the tendency to rapid explosion in rich mixtures may be reduced and in any case the explosion is of longer endurance; and in some circumstances stirring action will ease relief requirements by reducing the tendency to rapid vibratory explosion. It is possible that the effect of a given relief area could be improved to a limited extent by attention to the aerodynamic design of the orifice.

CONCLUSIONS

The investigation has indicated that as originally supposed, the occurence of crankcase explosions is likely to be associated in the majority of cases with the formation and subsequent ignition of lubricating oil mist in contact with an overheated engine part. An alternative explanation, still based upon the overheated part but not involving oil mist, is conceivable, however, if mechanical oil spray is present in the crankcase in explosive concentration. That this is so, at least in some engines, seems not unlikely and the matter calls for continued study. Nevertheless, the circumstances that would lead to explosion through this channel, without oil mist formation, are so special, that it is felt that mist formation can be taken as a criterion of explosive conditions in a considerable majority of cases.

The observation that the optical density of an oil mist at the lower explosive limit of concentration is very high, whereas barely visible mists arise in normal engine running, suggests that a warning system based upon the interruption of a beam of light in the crankcase, should be of very practical value. Such a system is now in course of development and shows great promise.

As an alternative, the direct detection of overheating through temperature-sensitive elements at suitable points in the engine may be considered. This has been discussed by Lamb[5].

The action to be taken following warning of abnormal mist formation or overheating would perhaps depend somewhat on circumstances. It is only necessary here to suggest that the warning might be automatically coupled with the release into the crankcase of carbon dioxide from an installation similar to those used for fire protection. This step would confer a substantial period of immunity from explosion in the crankcase during which steps could be taken to arrest the overheating and mist formation and finally to disperse the accumulated mist.

Explosion relief, as applied to the crankcase problem, has been shown to be a very complex principle. The work has shown, however, that the method has useful scope in protecting the crankcase from damage due to not-too-severe explosions. The indications are that in large engines no practicable relief area is likely to be too great and the most that is reasonably possible should be provided. If the passage of explosion from one crank chamber to another could be prevented, however, the duties of the explosion reliefs would be lightened appreciably. As regards the closure of the relief area, a bursting panel is likely to render the relief less effective than will a smoothly operating closure, such as spring-loaded plate valve opening at the same pressure. The opening pressure of the latter is also, in all probability, the more reliable.

In designing relief valves careful attention must be given to providing adequate means of retarding the plate or other moving part at the end of its travel. Certain commercial valves that have been tested, while effective in the relief of explosion having regard to their area, have sustained damage due to the momentum of the moving element.

Explosion relief, though capable, within limits, of saving the crankcase from damage is not of itself enough. Steps must also be taken to protect engine room personnel from injury due to the ejected flame. It is possible that in some circumstances the ejected gases could be ducted to a safe place of egress to the open air. Lamb[5] has proposed the use of gauzes covering the relief opening to suppress the flame, and it is possible that other devices akin to a flame trap could be used. Investigations into these various alternatives are being carried out.

REFERENCES

1. Burgoyne, J. H., Newitt, D. M., and Thomas A. 1954. "Explosion Characteristics of a Lubricating Oil Mist." "The Engineer," Vol. 198, No. 5, 140, p. 165.
2. Burgoyne, J. H., and Cohen, L. J. 1953. "The Production of Monodisperse Aerosols of Large Drop Size." Coll. Sci., Vol. 8, p. 364.
3. Burgoyne, J. H., and Cohen, L. 1954. "The Effect of Drop Size on Flame Propagation in Liquid Aerosols." Proc. Roy. Soc., Series A, Vol. 225, p. 375.
4. Margerson, S. N. A., and Robinson, H. 1953, "A Piezoelectric Recording Manometer." Ministry of Fuel and Power: Safety in Mines Research Establishment. Research Report 82.
5. Lamb, J. 1952. "Explosions in Enclosed Crankcases of Reciprocating Engines: Their Cause, Effect and Possible Remedy." Proc. I. Mech. E., Vol. 166, p. 327.

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SAFETY IS PRESENCE OF PLAN

THE AUTHOR

entered the Coast Guard from the State of Idaho and was graduated with honors from the U. S. Coast Guard Academy, class of 1927. He has served in various capacities aboard major types of Coast Guard vessels; as instructor, engineering subjects at the Academy; as Planning Officer, Coast Guard Yard; and as Chief, Engineering Divisions at New York and presently, Seattle. He has commanded the Cutters Tampa (renamed Saranac) and the Ingham.

His primary interests and the majority of his assignments have been in engineering. He has been most active in promoting safety within and without the service and is the author of several papers on this subject. He is a member of the Society of Naval Architects and Marine Engineers (currently vice-chairman of Pacific Northwest Section), The Society of American Military Engineers (currently President of the Seattle Post), this Society, and Tau Beta Pi, New York Epsilon.

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I HAVE a parrot who has been a member of my household for a number of years. His official name is Pancho, but my pet name for him is "The Beaconest Bird" and for a very good reason. He tore up the first two cages just to exercise his powerful beak; he didn't really want out. In fact when he is allowed freedom about the house, he will shortly return to his cage, and mounting to his lookout perch will chatter like mad, as if daring anyone to assault him, now that he is back in his castle. Finally, I built a replacement cage of quite heavy galvanized steel mesh. Now, if this cage is a place of safety for the bird, it is doubly so for the household, for it keeps his beak away from picture frames and chair backs, and his claws and wings from the curtains and bric-a-brac. It is a very efficient, double purpose safety device. But there is still one factor to be considered. The heavier gauge mesh is large enough to allow the easy passage of a human finger!

Now, why do people want to stick their fingers into parrot cages? Why do they want to thwart this safety device designed for their protection? No, I can't answer it either, but the temptation is very real and attractive, as has been demonstrated many times. Ask any zoo keeper! It is a significant discrepancy in *untrained* human nature to disregard safety devices. Experience, that dear, dear teacher, tells us: we must accord a side by side place to guards and attitudes.

We can avoid danger by staying away from cliffs, keeping off the highways, or retreating to the cloisters. But most of us don't choose such a pattern. We want to live full and interesting lives and have fun and excitement on the way. John Paul Jones said: "Give me a fast ship, for I intend to get in harm's way." He did pretty well, too, and came back alive. In a tight situation he was noted for his presence of mind. About 50 years ago, Thomas Fleming Day wrote: "Presence of mind might better be called, presence of plan." Today, many of us find ourselves in harm's way whether we intend it or not. But there is

a way to survive. We can face danger safely if we do either one of these two things: keep our minds on what we are doing, or keep a guard between us and the danger to protect us when our minds are blank. Both systems require thinking, a presence of plan.

There are thousands of applications of guards in use today, and more are coming. There is no end to man's ingenuity along this line, the results of this planning, thinking things through. It would seem, then, that we ought to be pretty safe, and we are, all things considered, but there is still room for improvement. If you don't think so, consider that in fiscal 1953 there were 2,571 marine casualties of sufficient importance to require reporting to the Coast Guard. In 138 of them 280 lives were lost. The direct and indirect costs make a staggering figure. I have looked over quite a number of statistical reports and accident summaries—don't worry, I'm not going to quote them now—There is one inescapable conclusion: The injuries and the losses stem predominantly from human failures, and these failure are mostly because people don't think before or while they act. They lack presence of plan!

I honestly believe that, as important as physical safely devices are, we will never reach our safety Mecca until we attain as individuals a safety consciousness. So long as men are less than angels, it is improbable that we will ever attain it down to the last man, woman, and child. But we must always face east! Our happiness, and even our survival in this fast expanding world of ours requires it. Most of what I will say you have heard before, but the psychologists tell us that it takes repetition, three to five times before things really sink in. As members of an enlightened group we should have presence of plan for safety, and it is my sole purpose to stimulate your thinking about it.

Recently, an engineman on a Coast Guard Cutter took up a floor plate. He knew the hole was there, and so did the others. Whom do you suppose got booby-trapped? That's right. Occupied with other thoughts he presently walked right into it. Now had he had presence of plan, he would have strung a reminder line to have kept his absence of mind from letting him down so suddenly. While he was triced up in traction for nine weeks, and in physical therapy for another nine, he had plenty of time to perfect his hindsight. Let's hope his foresight next time will be improved, but don't be too sure.

A vessel preparing to load cotton at a southern port removed four sections of hatch covers and three beams, and placed them handily on the remaining section of the 'tween decks hatch. The first load of cotton came down O. K., but when the sling went back up, it hooked the supporting beam, pulled it out, and dumped the entire lot of hatch cover and beams on the hapless longshoremen below. Now here comes the part of this story which is hard to believe. Only a few months previously, exactly the same accident, complete in every detail except for the injuries, happened in the same No. 5 hold, on the same ship, with the same officers! Think of it! How stupid can you get? We might excuse the first time, goodness knows we all make errors of judgment now and then, but the second time, that's inexcusable. And that's not just my opinion, either. The courts awarded the six victims a lot of the steamship company's money.

Where was the fault? These officers called themselves seamen, and had papers to prove it. The thing which distinguishes a seaman from a landlubber is his awareness to danger and his skill in the face of it. They failed on both counts simply because they had no presence of plan. Intelligent analysis and subsequent instruction and enforcement are the essential ingredients of a safety plan; good seamanship, too. Does it appear I am getting off the subject of safety by talking about seamanship? By no means! You cannot separate good seamanship from safety. That goes for every other profession as well. Caused accidents like this have been repeated countless numbers of times since Sampson pulled the props from under the temple in Bible days, and they will keep right on happening until we as individuals learn to think things through.

Gene Sarazen says, "Before I swing, I SEE the ball in the hole." Would that we could all be as successful in getting it there! For him it is no accident. He has his mind on it. It's all part of his plan.

A boat builder in New York tried to transport a good sized yacht through the city streets to Grand Central Palace for the annual boat show. Not only did the boat get firmly stuck under the 3rd Ave. el, but it did a lot of damage to the boat, and tied up traffic for several hours on that busy street. A little planning with attention to details would have avoided this fiasco. Contrast that performance with the Portland, Oregon concern which successfully transported a new Army LCM 72 ft. long by 21 ft. wide over the public highways four miles to its launching site.

Maybe they are smarter out west than they are in New York. Still, Baltimore Naval Architects put on false bows, blocked the car ports, lashed down everything that might have tossed about, and rigged towing bridles to defeat the dire predictions of the Calamity Janes of the water front that the overhung ferries Gov. O'Connor and Gov. Nice "would meet Davy Jones face to face in short order." Of course, they had a little West Coast seamanship along the 6,000-mile route. It all goes to show, when there is presence of plan, there is safety.

There are others, too, who have demonstrated it. Blondin walked over the Niagara abyss on a wire. He deliberately put himself in the most dangerous position imaginable: a narrow path, swaying and bouncing, and no handrail. One slip and death was certain. But he didn't rush into it blindly. He acquired skill on the low, short wire before he stepped out on the high, long one. And I'll bet he never once let his mind stray from what he was doing until he stepped safely down on the other side.

Houdini, time after time, escaped death. His successes were the direct result of his presence of plan,

and concentration. Fortunately most of us don't have to get out of a straight jacket under water or while triced up under a crane, but we can be trained to meet squarely the problems we have. Like Blondin, Houdini and Sarazen we can see the ball in the hole before we swing. That's part of our presence of plan. There's no monopoly on it. It's yours and mine, but never without effort on our part.

While I was serving on the Cutter *Saranac* down in the Gulf of Mexico, we received a distress call from a tanker. Her boilers were on fire, the machinery disabled, and the vessel was wallowing helplessly in the winter seas. After we arrived, I was sent aboard to get the facts for our official report. Being an engineer I naturally went below for a first-hand look. The fire was out, but the handrails were still hot, and the whole place was a blackened mess. Had a gang of vandals boarded the ship with acetylene torches they couldn't have done a better job of wrecking the upper sections of the boilers. You didn't need to take off the air heater casings or remove the breechings. You just looked in where they used to be. The air heater tubes were at least 50% consumed, and the burnt tube ends hung down like macaroni, very well done.

This tanker was on its initial trip south after complete reconditioning, during which the engineering plant was improved by the installation of air preheaters. Soot blowers were installed, and might have done the job intended, but the operating personnel were not instructed in their use. In fact, no instructions were given concerning the new responsibility of maintaining the air preheaters. It did not occur to the engineers, or those who had the papers to prove it, that there might be a soot fire hazard until the roar of the fire and the red hot casing drove them out of the machinery space.

I do not know what the repair bill for this job came to. But we towed the tanker to Todds, Galveston, and Todds didn't work for peanuts, even back in 1938. The vessel was laid up for several weeks. Instead of making money on that first trip down for Texas oil, she cost the owners a pretty penny. Now where would you place primary responsibility for that casualty? On the design engineers? Hardly. On the Chief Engineer on board? Perhaps. On the company's port engineer? We are getting closer. On the top management who decided to add the economy units to the vessel? That's the place! Sort of a drastic conclusion, don't you think? Well, let's look at the *whole* problem. Instead of high level policy to insure safety in operations, one that included an instructional and training program right on down the line, it was assumed that everyone knew his job, and that he would do it without any particular supervision or special instructions. From the information I obtained, there appeared to be no effective program, recognizable as such. It was every man for himself. There was no presence of plan.

Lord Nelson said: "England expects every man to do his duty." This is high level policy, all right, and acceptable in principle, too. But when you pin down a fireman, the engineer watch officer, and the chief engineer, as I did aboard that tanker, and ask each, "What is your duty?," and he answers, "I don't know, nobody told me," the high-sounding phrase has very little meaning.

Unless management understands that pressure for safety must be made effective at all levels by supervision, instruction, persuasion, discipline, and enthusiasm, it should be no surprise when "operation fiasco" becomes by default the order of the day.

You've all heard of the man who sits on the far side of the limb and saws next to the trunk, and the one who paints himself into the corner away from the door. We chuckle over these comic happenings. But this one is not so comic. Two seamen, with air hammers, were chipping paint on the boat platform of a tanker during nice weather at sea. A safety line had been stretched along the ship's side, just in case. Instead of chipping from the ship's side inward, one of the men was working outward. His partner spoke to him about it, and suggested that he turn around, but the work went on as before, the two men working back to back. Shortly, the noise of the second hammer stopped, and upon getting to his feet, the man who was working inboard saw the other in the water, fast dropping astern. He had backed himself right over the side, under the safety line! Despite a prompt "MAN OVERBOARD" and a six-hour search, he was not recovered .

Our examples show, and statistics prove that most accidents are caused by our failure to think; that is, to think deeply enough; to see more of the whole picture. Even when we think we are thinking we are often just day-dreaming or toying with the realities of our situation. The man who backed over the side surely must have thought about his situation after his partner called it to his attention, if not before. But his thoughts probably ran like this: "Oh, I'll be all right. I'll know when I come to the edge and I'll stop. Besides, there's a safety line there. I know what I'm doing; why does he have to butt in? I'll make my own decisions! Anyway, it won't happen to me." Famous last words! Now had he had presence of plan, his thoughts would have run more like this: "Gee, it's a long way down to the water. I'd hate to fall in. I know it's cold, even if the sunshine up here makes it warm. Supposing a shark should get me before they can lower a boat? Supposing they don't get me? What will Mary and the kids do? Bill's right, I'll turn around now before it's too late." Yes, had these been his thoughts he would still be working today. I am sure of it, for his pattern of thinking, his presence of plan would insure his continued survival, and he would truly be a valued employee.

Do you think people actually resist safety measures and instructions? I do. We resist for exactly the same reasons we resist other things and ideas which are presented for our betterment. It's not that we have anything against safety. It's just that we are not able or willing to think things through. As with religion, we lack understanding of the goals, and are re-

luctant to be bothered with the uphill climb to reach them. And it is an uphill climb to achieve presence of plan for safety.

Mahatma Ghandi said: "God himself dare not appear to a hungry man except in the form of bread." The pearly gates and the streets of gold do not satisfy the immediate demand for food. The need is for something he can sink his teeth into, and right now. He rejects everything else. So it is with safety. Those of us who would carry the safety message to Garcia must learn that unless we present ideas in terms of the other man's needs, his immediate needs, he will reject them as inapplicable. He may admit they are fine for the other fellow, and maybe for him in the vague tomorow, but for today, he can't be bothered.

Kipling put it this way:

> God and the shipbuilder we adore
> In time of danger, not before.
> With the danger past, and all things righted
> God is forgotten, and the shipbuilder slighted.

We resist instruction because we are reluctant to try a different way. We tend to cling to what we have. We resist if there is variance with our past experience, and we downright disbelieve if it differs from what we have been taught. We like to be free to make our own choice. We resist, if we fancy it smacks of regimentation . . . the parrot cage, for instance. For 2000 years at least we have been saying: "Let us alone, what have we to do with thee."

The list of reasons why we resist safety is long and involved because it is a cross section of human behavior. For our purpose here, I think I can sum it up in the one reason which suggests its own remedy: Safety is not understood. It has been said, there is no such a thing as a dull subject, only dull teachers. Until we sharpen up our teachers and our teaching methods, we need expect no miracles in overcoming these resistances. Millions of words have been written and spoken about teaching by others more competent than I, and so I am not going much further into it now. But I do hope to leave you with a keener appreciation of the problem; sharpen you up a bit; help you to carve out a plan.

One of the reasons why safety is not understood is that it is frequently presented in terms of statistics . . . so many killed, so many injured, the fire loss was so many dollars, and so on. A blow by blow description is more stimulating and will be remembered longer than the single announcement that there was a knockout in the seventh round. Statistics are announcements. To make them effective in our teaching, we have to go behind the neat columns and give a blow by blow description of what they mean in terms of less meat on the table, the short vacation, or none at all, the hospital suffering, the graveside grief, the struggle for a livelihood of the widow and the orphans. Statistics must be made into men, women, and children, folks like you and me, really nice people if you knew them. Until they can be seen in this light, we will never get very wrought up over safety and we will never be able to put it across to others. This is an important link in our presence of plan.

Most of us are indifferent in our attitudes towards the other fellow's tragedy, because it doesn't touch us or our experience. We hear the newsboy shout, "Bus crash kills 17; read all about it!" and we do, because we thrill to the excitement, and it's not our problem. We say, "That is life," and let it go at that. Then tomorrow brings another item, and yesterday's is forgotten.

When you and I read about a ship sinking, it comes a little closer to us, specially when it carries a Captain Carlson. We, who have been to sea, understand about such things. As Will Rogers put it: "We are all ignorant, just ignorant about different things." We are not ignorant about ships. The sinking and the loss of life is no mere statistic to us. We see the mountainous seas; we feel the shock of the cold water; we hear the whistle of the wind in the rigging, the roar of the storm and the sting of the salt spray. We sense the personal loss of pride and the empty feeling in the pit of his stomach as the Master is forced to shout: "All hands abandon ship!" We may even wish we could have been there to have helped out.

Well what are we going to do about it? Just what part can we as individuals play to prevent tragedy at sea? This is the question which must be answered, or our time will be all but wasted.

First, let's have a closer look at ourselves. What concern is it of mine? Let sleeping dogs lie. Let the professional safety people handle it. I can't be bothered. I've got a full time job, besides, safety is not my bailiwick. Does this sound familiar?

The promotion of safety does concern you. First of all, because others are depending upon you, look up to you for leadership and guidance, and in the performance of your jobs for them they are trusting that you have their interests at heart. You may not have thought about it in this way before, but you are your brother's keeper when you send him out to sea on a ship that you have designed, or built, or repaired, or inspected, or insured, or for which you have furnished equipment. And the training he receives, and the shipmates you choose for him have a definite bearing on his safety, as we have seen. Most of us are managers in one sense or another. The responsibility is ours; we cannot dodge it. Safety is our concern!

The accident is over and done with, forget it and go on! But should we? Hardly! Had the officers on that cotton ship analyzed their hatch stowage problem after the first accident the second would not have struck down the six stevadores, and ruined their own reputations as seamen, and bled away the company's profits. And had there been presence of plan for safety on the part of the company executives they would have taken action to pass the saving word back down the line. With your experience, your analysis is essential to proper solutions, and many of you are in positions where your pressure for safe practices is worth its weight in gold. We should not let sleeping dogs lie!

It is true, especially in handling personnel, that the professional safety man can make the major contributions, at least those which produce the greatest showings. But he requires your backing. And then, there are many of you who work in organizations which are too small to afford a full time safety specialist. Since you are not bound by him, the sky is the limit for your efforts. Let's not seek shelter behind the backstop while the professional people play. Let's get in there and bat and run and pitch with them. If you think you are too old for all that exertion at least you can umpire the game, and that in fact is where the manager best fits in safety planning.

Do you sleep soundly at night, now that middle age is creeping up on you? Do you take more of your problems home with you at night and count them as sheep over the fence? The knowledge that you have done your part, that you have been "the good and faithful servant," may not assure the abandon-care sleep of a child, but it will avoid the nightmares you might have from knowing that you could have prevented a tragedy but couldn't be bothered. Little things are important. In taking action, remember, you cannot start too soon, because you never know when it may be too late.

So you've got a full-time job? I think that goes for all of us, without question. I am not asking that you leave all and follow the professional safety line. I am calling your attention to the fact that you cannot separate safety from your job. The railroads go so far as to require: Safety First. Others are less emphatic, but you must agree that the safe way is the right way. As I have already pointed out, safety is an attitude. You can assume it and make it a part of your full-time job. We all want to eat regularly, to have things for our families, and to sum it up, to enjoy prosperity. Then business must prosper, and it takes men-on-the-job to accomplish it. When the place doesn't burn down, and when the stretchers remain stowed at the first-aid station, they can stay on the job. Whether you own your own business, hold stock in it, or just work there, safety is indeed your bailiwick!

Right about now, you are no doubt thinking: "What can I do? It's alright for a Captain to talk—he just orders it done, and they have to do it; but me? I don't cut that big a circle." Confidentially, I'll let you in on a secret. I don't either, and the fact is, few of us do. Even the President of the United States has his hands tied in one way or another. Think how frustrated he must feel sometimes, when he, as head of our government can't dispose of even simple problems without a battery of consultants and precedents tieing him up in red tape. And so, just because we don't have a free hand to solve or direct the solution of the safety problems we see, doesn't mean that we should do nothing about them.

In Seattle, the Coast Guard rents the top floor of a parking garage at 4th and Columbia. The bottom flight of stairs has 23 concrete steps in a straight descent, and no handrail. We requested the owner to instal a handrail, but his answer was to the effect, No, not interested. Since this is a leased facility, our regulations prevent our spending the money to install the rail, even though the owner was agreeable and suggested it. We were stymied, and for some time nothing was done. One day, while descending with my hands in my pockets, I reached the landing above the long descent, and suddenly galncing down, I could see that bone sticking out of the forearm, and smell the ammonia. Out came my hands, and as I again counted off the 23 steps, I said to myself, "Am I really doing what I can to correct this situation"? By the time I had reached the bottom, I knew that it was within my power at least to post the condition, and that's just what I did. When I got to the office, I had the draftsman make up a big sign and run it off on the Ozalid machine. Now, garage employees and Coast Guardsmen alike are greeted at the upper landing by:

THIS STAIRWELL IS WITHOUT BENEFIT
OF HANDRAIL. KEEP HANDS OUT
OF POCKETS. KEEP ALERT.

I slept better that night.

As you go about your work, yes, and while to and from it, and at home as well, ask yourself, and get others to ask themselves, "What am I doing to correct this situation"? You'll be surprised at the weight you can throw around with the muscles of your strong attitudes. Come to think of it, when you count up the number of people your life touches in a direct and indirect way, you do cut quite a big circle, after all. Consider Pi r square. That little r in your presence of plan can be a mighty big dimension in your circle for safety. And you have complete control over it.

I have suggested the part you, as individuals, can play with your presence of plan for safety. But no safety article would be complete without considering another broad avenue of approach. When you want to make really big gains, you set up a program, and enlist the participation of as many persons as possible. A safety program is presence of plan on a big scale. Although safety programs are usually associated with large organizations, there is no reason why a small outfit can't profit by the principles involved. Formal or informal, it can still be effective if you will make it so.

Taken as a whole, the Coast Guard is a big organization, but because we are so spread out, we are really a lot of little outfits with a central control. Except as it stems from the central control, we have not found it expedient to have a formal safety program. Instead, at each operating unit we have a safety committee, democratically composed of both officers and enlisted men from several departments, such as operations, engineering, and commissary. Most committeemen are appointed by virtue of the job they hold, thus their backgrounds have little special training as

safety men. Sometimes a man becomes a member because of his enthusiasm. He is generally one who has had an accident, or has otherwise seen the light. Then again, he may be a problem man; his attitude is less than what it should be, so he is appointed to the committee in the hope that his activity there will convert him, and it usually does. The unit is supplied with safety promotional material from the District Office, and the Commanding Officer, or officer-in-charge, working with his committee, carries on from there. Once a month, or oftener, if there is a pointed need, the committee meets and discusses one or more problems at the unit—their own unit. If it is a training or instructional problem, or a hazard capable of their own correction, they tackle it during the month. If it is a problem too big for them, they pass it to the District, and if too big there, it is passed on to Washington, D.C.

There is a Chinese proverb which says: "A man removes a mountain by carrying away small stones." Our anti-safety mountain is not nearly so high or formidable now that many men are handling its small stones.

One of the things which has pleasantly impressed me since coming to the Northwest is the profusion of growing things, and especially the rock banked terraces where fresh new blossoms successively appear throughout the year. You gardners know that to have an abundant yield you have to spade up the whole place about once a year, and in between showers must cultivate to keep the ground soft and the moisture in. When there is not enough rain we irrigate. Now and then we rake in a little fertilizer. This magic formula makes everything grow, so we have to get down on our hands and knees and uproot the weeds. We shape, we trim, we transplant; we put up fences, and signs saying: KEEP OUT. But the bugs can't read, so we go after them with sprays and powders. We throw rocks and yell at the neighbor's dog, and lead his toddler by the hand, selling him a bill of goods all the way about how nice his own yard is to play in. Gardens demand a lot of attention, but they bring a lot of satisfaction, too. Wherever you see well tended gardens, you may be sure there are solid citizens behind them.

What have gardens to do with safety? Simply this: A safety program is just like a gardening program.

Once a year we spade up the whole place with an all-out campaign, perhaps an accident-free month. All the rest of the year we keep things stirred up. If there's not enough natural rain—that's interest; and there seldom is—we irrigate. If the results seem lean, we fertilize with fresh ideas. We pluck the weeds—unsafe practices—while they are still babies, so they can't grow up into bad habits. In so doing, we make room for good habits. Where there is a tendency to slide, we stabilize the slopes with rock-like rules and regulations. We transplant things and men when they are incompatible. We erect fences, install guards, place signs. We take out after the dogs, those rascals who race pell mell without regard for their environment. We lead recalcitrants by the hand with patience; we explain what it's all about. Those organizations and those compaines which have a safety program are the solid citizens of our industrial age.

The song says: "One had a shovel and the other had a hoe." Some do it by hand, and others have a put-put, depending upon their needs and means. So with safety programs. Some are formal and some are informal. Each adopts those measures which best meet his requirements, while following the same basic principles. You raise carrots, celery, snapdragons and petunias by about the same rules, and you run a railroad, a ship, a factory or a shipyard, safely, the same way. The good earth and the good people are your productive mediums.

In keeping up with the Joneses, even if it pinches a bit, safety, like suburban gardening, has become a way of life. It is nourished by our increasing prosperity, knowledge and pride. It is fast becoming an ideal and an obligation in our enlightened human relationships. But there are still plenty of people who think gardens are strictly for the birds. They can't be bothered; the effort is not wothwhile. They are content to live in their slums with barren yards. Our self-appointed task and the answer to: What can I do about it? must be to introduce and persuade them to the beauty, the peace of mind, the rightness of the way of life, of a safety garden. It's a job for solid citizens, and that's certainly us. It's part of our overall presence of plan.

One other observation. No well ordered garden and no effective safety program will prosper unattended. It takes work, hard work, by interested and intelligent people, and they must keep everlastingly at it.

Who are these interested and intelligent people who run a safety program? They are, first and most important of all, the policy makers, top management. Large organizations will have a safety director with staff; smaller ones will have him without staff. Still smaller ones will omit him and depend upon the supervisors normally directing operations. It stands to reason that, if people won't think for themselves, and thereby commit unsafe acts, we have got to get someone else to do the thinking; someone who stands a bit aside and can see more of the whole picture. That definition just fits the supervisor, and he is the one who can make or break the program. As we have seen, normal practice should exactly dove-tail with safety, for the right way is the safe way, and the safe way is the right way. That ought to make it easy, but it's not, because, it seems, we behave like human beings. It has been amply demonstrated that supervisors need help, and lots of it. Theirs is a difficult position, one which involves leadership and followership, and these strategic attributes seem always to be in short supply. To secure them even mildly requires everything the textbooks have produced so far, and more. It is management's job to foster the supervisor's training, and see to it that he really supervises. That's no small assignment, either. Just saying so won't make it so, as we shall see.

A portable ship's rail consisted of a steel cable, and was entirely satisfactory as to height and strength. But the day came when it was badly rusted, and the inspecting officer ordered it renewed because the broken strands were a definite hazard to the hands. The word was passed. The supervisor considered he had done his part. The section was removed so as to transfer the fittings and secure the measurement for the new piece. No relief span was strung, and within an hour a man fell overboard. Fortunately, he was fished out, surprised, but unhurt. He had depended upon the little rail that wasn't there. There are hundreds of cases on record analogous to this. Supervisors must supervise all the way. They must follow through if they would supply the missing links in the safety chain. That is literally as well as figuratively true in our case of the rail!

The mechanical engineering problem of stopping the boat hoists just short of two-blocked was nicely solved by the installation of limit switches, or so the designer, the manufacturer, the installing shipyard, the purchasing authority, the master and the mate all thought. A vessel tied up at an East Coast pier had completed testing her lifeboats by lowering them to the water, and had raised them up to the davit heads again. One boat needed to be hand cranked an inch or two to bring it to its proper nesting place. The Chief Electrician happened by on deck, and the A.B. asked him to lend a hand on the crank a moment. "Sure, I'll help," he said, but instead of taking hold of the crank, he stepped to the electric control box, opened it, and with his trusty screwdriver shorted out the limit switch. The hoisting motor took off; the boat came up until the blocks met; the falls parted; and the boat fell into the water. His screwdriver fused so firmly from the overload current he was unable to release it in time.

The repairs to the boat, to the electric circuits, and the renewal of the boat falls cost quite a bit. How fortunate there was no one in the boat at the moment, as there might have been. You would think that you could depend upon your safety devices, and leave the matter there, but the fact is, you cannot. Here is our parrot cage again. Mechanical engineering has got to be aided by a lot of human engineering before we can begin to rest easy. Failing to recognize this puts the manager in the same position as the ostrich with his head in the sand. If he doesn't learn, after a rude awakening or two, we may suspect that his head may not be in the sand after all, but that the sand is in his head!

Following the usual pattern, this accident was man-caused. Unlike most accidents, it was caused by one who knew better. A TRAITOR, that's what he was. This Chief Electrician was no small-change workman. He was a well-paid supervisor and in his line was well versed in safety. Unfortunately, not well enough! Barnum told us: "There's one born every minute," and our continuing concern, our presence of plan must be to indoctrinate them as they grow up, and when they get to be supervisors, *we still must not stop,* lest we fall short of: well enough.

955 lives and the complete loss of the vessel is a pretty dear price to pay for poor housekeeping, but these are the facts. Poor housekeeping is more than a confusion of things. It is an attitude. The skipper who permits it will invariably be found lax in attending to the day's work, the details of the organization, and in enforcing discipline. He is a poor supervisor; he lacks presence of plan. That was true on the General Slocum in 1904, and it was true on the Naronic in 1949, and on many other ships during the intervening 45 years. Even in cases where there has been no general disaster, lesser events have established that higher operating costs, higher accident rates, and general absence of supervision are corollaries to poor housekeeping. It's comparatively easy for us to brush off poor housekeeping as poor management on the part of the operators, but that doesn't solve anything. A place for everything has to be provided before everything can be in its place. If you designers don't plan it, and you shipbuilders don't fabricate it, and you managers don't require it, it won't be there. If you force the skipper to say, "What's the use, where can we put things"? the attitude will be contagious right down to the deck hand and oiler. You can create compartments and spaces of the size and location needed, you can provide suitable access, adequate lighting, and functional painting. Not only can good housekeeping be made easy, but the atmosphere can suggest it. Take tool boards, for example. Three or four metal or wooden drawers are a common engine or boiler-room improvision, into which hammers, files, tinsnips, wrenches, rags and coffee grounds find their way. Create a varnished or painted tool board with clips for every tool, and you almost miraculously bring order out of chaos. The board speaks for itself, and you have gained your point in the training program. Since the boys are going to have their coffee anyway, why not provide a nice, white, sanitary metal cabinet and coffee maker? The problem of policing up the area will still exist, but the supervisor doesn't have to take "No!" for an answer. If he does, then management has a justifiable reason to administer the usual pat on the back a couple of feet lower down.

Neither you nor the managers and operators of our ships want people to get hurt. But the object of being in business is to make money. There is little doubt that there is more concern about the possibility of one's own broken pocketbook than about the possibility of a broken arm or neck of your customer, or your customer's customer. Obviously, you are under constant pressure to keep costs down and this is in conflict with rising costs, everywhere. Compound the generally increased cost of doing all classes of work with the new requirements modern safety practices demand, and it is appreciated you have quite a problem on your hands. However, along with the rising costs is a more liberal sharing of the operator's wealth, enforced by the courts, when there is an ac-

cident. This is one issue we cannot dodge, but we can alleviate it by having presence of plan—a safety consciousness—when decision time comes 'round. Safety is profitable. If this article was written by an underwriter he would produce tables of statistics to show it. But I have another example:

Some time ago our Seattle office received a request for annual inspection of a vessel. The gangway consisted of two 2 x 8's with but three cleats, and these on the underside. There was neither handrail nor grab line, and at this stage of the tide, the planks were too steep for mounting, except on all fours.

The inspector insisted that a suitable gangway be rigged, but the master 'lowed as how this same arrangement has been used for four years, and this was the first complaint he had heard of. He took no action. It just so happened, the vessel's owner came aboard, and at lunch the matter was presented directly to her by the inspector. Upon the advice of the master, she ruled it adequate, that she would not spend money so foolishly. It came time for her to leave, and the master gallantly suggested that he proceed her to assist. "Nonsense, I'll just turn around and back down, like I came up." This unseamanlike and unladylike posture was funny for a moment, and then it happened. She caromed off the pier stringer, struck the ship's fender, and plummeted, unconscious, into the water. Fortunately, oh how fortunately, there was a number of persons present to help. A deckhand immediately went over the side to support her head out of water while a sling was rigged to hoist her out. She escaped skull fracture and drowning, but the broken shoulder and collarbones gave her several weeks in which to think over the inadequacy of the long-used, improvised gangway. But, as you may have already guessed, the ship didn't have to wait even that long before it was provided with a proper means of boarding.

Suppose someone other than the owner had taken that tumble. And suppose it might have occurred at night with no other person at hand to effect a rescue. Would the resulting lawsuit have been easy on her purse? In fact, how about her hospitalization? Foolish expenditure, she had said, echoing the master. Was this master and this owner different from most other folks? No indeed! You and I just as frequently need a brush with death to remind us that safety pays, that the safe way is the right way, that we must think things through, that we must have: presence of plan, for safety.

After every catastrophe, you always hear the cry: "There ought to be a law against it!" It is truly said, "the regulations are written in blood." But if you think legislation to supply well proved needs comes easily, consider this: On 24 July, 1915, the *Eastland,* lying at her dock at Clark Street in Chicago, rolled over. 811 passengers and 1 crewman lost their lives. The *Morro Castle* burned off the New Jersey coast the night of 8 September, 1934 with 124 dead. The *Mohawk* sank, also off the New Jersey coast on 24 January, 1935, and carried 45 to their doom. The Congress, spurred on by the last two disasters, finally got around to passing enabling legislation to require the approval of plans and specifications for passenger vessels before alterations or new construction was begun. What was the date? 27 May, 1936. What was the bill? It was word for word with the bill originally introduced following the *Eastland* disaster. The delay was 21 years—a whole generation!

We recognize that men are ignorant, petty, selfish, greedy, and downright cussed, and so we rightfully must have laws to protect us from their depredations, but one of the great difficulties our society is facing today is the increasing complexity of those laws, our government. Although we often say, There ought to be a law against it; should there be? Do you know how much will it cost? Can it be truly enforced? Do we want to abide by it ourselves, or are we just proposing it for the other fellow? Can government take the place of individual responsibility? No, it cannot, if we are to remain a free people. It's up to us to regulate ourselves more and our neighbors less. The advantages of this system are many, among them: it takes no legislators, no policemen, no lawyers, no courts, no jails. The opposite is true with the "There ought to be a law against it" philosophy. I am not advocating that we ought to do away with punitive laws, nor that we should pass no new ones. But I would like to point out that merely having laws on the books does not insure obedience, and even punitive measures fall far short of accomplishing safety.

It is necessary to the proper performance of our duties to know what the law requires, or at least where to find it. The average one of us does not have either the time or the legal training to wade through the statutes. Fortunately we don't have to, because one of our public minded Coast Guard officers, Commander Frederik K. Arzt has compiled a 1200 page book entitled: "Navigation and Safety." It is a practical and accurate manual for all who have occasion to refer to the marine laws of the United States. This entire book is on the up-to-day aspects of the law as it affects the safety of ships and seamen. You don't have to leaf very far through it to realize that the exponents of: "there ought to be a law against it," have had a pretty good field day, already.

Let me repeat: you cannot secure by legislation, nor by fear of punishment alone, obedience to safety laws. You can only approach that goal by safety education, and more of it, and by a general increase in moral stature which benefits us all around. It keeps us facing *East.*

The Coast Guard is not alone in its efforts to keep maritime safety at the fore. I am not going to attempt to mention all the other organizations, lest I leave out some deserving ones. But no article on maritime safety could be complete without calling attention to these devoted people. Perhaps the oldest, and still today the most outstanding are the classification and technical societies. Worldwide, they have bridged

the barrier of international politics and languages with their presence of plan.

The national Safety Council and its many affiliates is diligently trying to secure the cooperation of management to achieve proper safety attitudes.

The underwriters' requirements produce a very salutary effect, for if you want your insurance, you'll meet his deficiency list, and he does not stop there, but joins with the oil companies, and many manufacturers of marine products in supplying a continuing barrage of instructions, pictures, posters, and movies to foster safe practices, and to help the supervisors supervise. It's all part of a grand plan.

The promotion of maritime safety is a king sized job, and fortunately, we knights of the safety round table are equal to it. The fight is not won, nor, as I pointed out before, can it ever be, but we are making progress. We are securing audiences in high places and low. We are overcoming resistances that seemed insurmountable a few years ago. Our followers no longer are few, and they are increasing in number and stature every year. The pump which puts on the pressure to create this high velocity is the genuine desire to serve humanity. That's reflected in the grand plan, too. Guided by engineering and teaching know-how we have in effect an educator which is pulling a lot of water out of the double bottoms of ignorance and indifference. Along with our building codes we are adopting a moral code for safety, and are setting the example by our actions. We are thinking. We are sharing ideas. And this is not like dividing our material substance, where each gift lessens the stock on hand. When we share ideas, we do not divide, we multiply. Think that over again. We do not divide, we multiply! Good ideas have legs. Once they get started, they walk all over the place like a chain reaction. They carry away a lot of small stones. They help us secure a presence of plan.

When the *Morro Castle* was burning, many of those who died were trapped in their staterooms. The passageways were either on fire or serving as flues for the fierce flames and smoke. A doctor friend of mine was on board one of the rescue craft lying alongside the burning vessel. He told me he longed for the authority to take his hypodermic needle and go along the portholes—for out of each was thrust a screaming human head—and put the suffering ones mercifully to sleep. Instead, he had to stand by helplessly and watch as one by one the screams were silenced as the roasting bodies plumped back into the burning staterooms. I was only a two striper then; I couldn't do anything about it, either. When Abraham Lincoln first saw the injustices to the slaves at New Orleans he resolved: "If I ever get a chance to hit this thing, I'll hit it hard," that's the way I felt about passenger safety then, and that's why I'm writing about it now.

I am not asking that each of you go out and get a soap box and start your own safety revival. True, that's one way, but probably not the best for either you or me. Leave that to the professionals. Budda said, "What we think, we become." What I ask is that you think deeply and sincerely about safety. See the bones sticking out, hear the screams of the roasting passengers, feel the ice cold water about you, see the set face of the widow and the appealing eyes of the youngsters clinging to her skirts and looking up from under her arms. If you can see and feel these things, safety will become top man on your totem pole. You will gain a safety consciousness, your presence of plan.

When I was a youngster, like most kids I had a cat. He was a pretty good mouser too. One day, rummaging in the back closet I saw a mouse run. I called the cat and then started moving things. The mouse ran into a rubber boot that was lying on its side, so I up-ended the boot quickly. I wondered just where I could liberate the mouse so the cat would catch it, and decided upon the brand new bathtub. With the cat under one arm and the folded-over boot under the other, I made for the bathroom, closed the door, put in the stopper and lowered in the cat. He immediately jumped out, but I put him back in again and then shook the boot. To my amazement, out came not one, but seven mice, and there was some mad scrambling as they scattered and tried to climb up the sides of the tub, only to slide back down again. Over and over they tried. There was only one possible place of concealment, and after a few moments of confusion, the mice all found it. Where do you suppose it was? Under the cat! He made absolutely no attempt to catch or harm them, but just squatted there and let the mice dive under him. I was thoroughly disgusted with my wonderful mouser!

Now it is clear to me what happened. The cat was confused by seven mice in action all at once, and with me standing over him to prevent his jumping out, so he just sat—and did nothing.

Men are not much different from that cat when they are faced with a lot of problems all at once. We need to catch one mouse at a time, not seven, and freedom to do it. In safety promotion there are so many items to consider, and they are so bound up with our daily work and play and travel, that there is confusion as to just what should be emphasized. Also, we have to keep peace with those who stand over us, control our budget. And so, we mostly just sit, hoping the problems will solve themselves, or at least stay out of sight, with not more than their tails showing.

Newton gave us the clue: "To every action there is an equal and opposite reaction." . . . Edmund Burke said: "All that is necessary for the triumph of evil is that good men do nothing." . . . Jesus said: "Blessed is he who seeth his brother's need and supplyeth it."

Safety is presence of plan and you are the planners. It's up to you!

THE DESIGN OF ECONOMIC TRAMP SHIPS

ACKNOWLEDGEMENT

This article, as published in the October, 1955, issue of "The British Motor Ship," consists of extracts from a paper presented at the Autumn Meetings in Yugoslavia of the Institution of Naval Architects on September 21, 1955. The author was E. C. B. Corlett, of Burness, Kendall and Partners, Ltd., marine consultants, London.

THE YEAR 1955 has seen a marked movement towards the expected and long-awaited replacement of war-time standard ships and obsolete pre-war tonnage, and Figs. 1 and 2 give a plot of the types of tramp ship ordered in the last three months of 1954 and the first six months of 1955.

The type of tramp ship that the owners of the world generally favor at the moment emerges clearly. In general, the ships are structurally arranged as closed shelterdeckers,

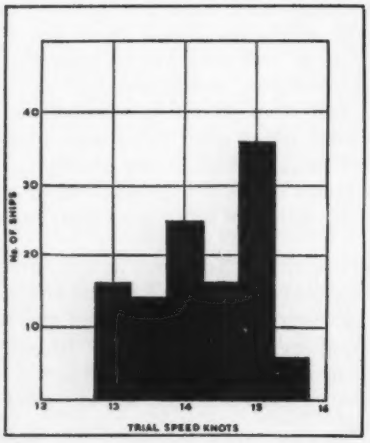

Fig. 1. Trial speed of some motor tramp ships ordered 1954-55.

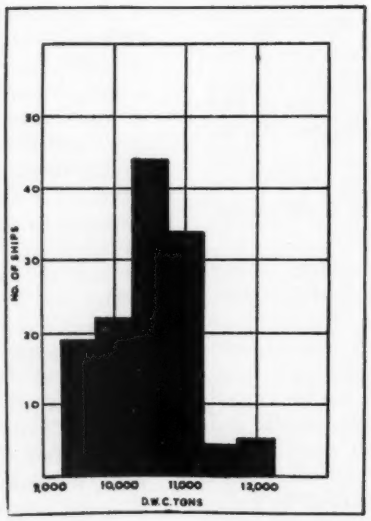

Fig. 2. D.W.C. of recently ordered tramp ships.

but operated normally as open shelterdeckers of approximately 10,500 tons deadweight. The permanent closing of the tonnage openings enables approximately 2,000 tons of extra deadweight to be carried. Speeds in general show an improvement over earlier tonnage and the statistical mean appears to be of the order of 14½-15 knots trial speed.

Using simple methods, one may arrive at an optimum speed for the carriage of, say, 10,000 tons of cargo on a standard voyage of, say, 8,000 miles. Fig. 3 shows the relative cost per ton-mile worked on this basis for different speeds for a modern Diesel ship burning boiler oil.

It is apparent that the optimum speed derived from this analysis is in fair accord with the mean shown in Fig. 1, and this would indicate that the average choice of speed of modern tramp owners is, in fact, approximately optimum for present-day conditions. The choice of deadweight is a more difficult one as it does not depend upon any basic mathematical analysis, but rather upon an analysis of the cargo that has been lifted in the past few years, together

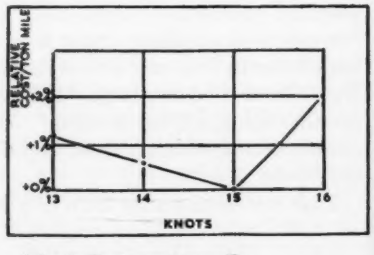

Fig. 3. Cost per ton-mile.

with the quantities which could have been carried. The steady trend towards the size of the tramp shown in Fig. 2 can be taken as representing the average opinion of owners based upon conditions of world demand and availability of materials for shipment, and it is probable that any considerable deviation would produce an uneconomic ship. If too small, a ship would not have the requisite bulk earning capacity, and if too large, she might often fail to collect a full cargo, as this may not be available at any time at the port of shipment, while waiting for it would entail such charges as to more than offset the improvement in revenue resulting from obtaining a full cargo.

After the deadweight, speed and cubic capacity required comes the question of how to achieve these figures. It seems to the author almost impossible not to have a very strong technical bias in favor of the Diesel-engined tramp ship. The weight of modern exhaust turbocharged Diesel machinery compares favorably with that of the best steam installation, while the weight of bunkers required for a given voyage is probably under half of that of such a steamship, both ships burning Bunker C Fuel. The influence of this cargo deadweight displacement ratio is noticeable, and Table 3 shows an outline comparison of four ships, all 14-knot service speed tramp ships, one steam turbine, one steam reciprocator, and the others Diesel, for a voyage of 12,000 miles.

However, it must be realized that the orthodox Diesel ship will probably show a slight decrease in cubic capacity per ton deadweight available due to her larger deadweight, but with the use of pressure-charged machinery the engine-room can be reduced to a size rather smaller than that of a steamship with a triple expansion engine and an exhaust turbine. With turbine installations, the space occupied is admittedly small, but no smaller than is taken up by a pressure-charged Diesel engine-room. Owners often state that difficulties of maintenance and shortage of Diesel engineers rule out the possibility of using Diesel engines. The flaw in this argument is that the economic margin between the Diesel-engined and steam-engined ships is so great that an owner building a new tramp ship can well afford to employ specially picked and trained engineers versed in the particular make of Diesel he is fitting to his ships and still maintain most of the advantage that he would expect to get financially from the Diesel engine. When one considers that steam machinery in a tramp ship probably costs at least as much as, if not more than, Diesel machinery, and that the savings per annum on fuel costs with the Diesel engine is of the order of 30% of the total cost of the prime mover, one can see that perhaps heavier maintenance costs cannot account for more than a fraction of the margin and, indeed, should not be a high figure with engineers specially trained as previously suggested.

Next, an owner must consider cargo handling. In the author's opinion, far too little attention is paid to this aspect of ship design and, in fact, it is somewhat salutary to reflect upon the relative influence of cargo handling and speed of turn round on the one hand, and economies in propulsion on the other, on the general overall economics of running the ship.

Let us presuppose that an owner has the projected form of a 10,500-ton ship tank-tested and that thereby a 5% improvement in e.h.p. is produced. This is quite a large amount by tank standards and would produce an economy per annum of the order of £1,500 in fuel cost. Now, consider a 5% improvement in speed of turn round at port produced by more efficient cargo-handling appliances, by choice of dimensions of holds and hatches, and by careful attention to detail throughout; presupposing a saving of one day in 20 in port, one can arrive at an overall assessment of the effect on the annual economics of such a change, not the least of which is an increase of 6% in effective ton-miles per annum.

It will, therefore, be recognized that cargo handling is a subject to which a great deal more attention must be given. Hatches must be opened quickly and easily. When carrying grain cargoes, feeders, trunks and shifting boards must be arranged quickly and simply with the least amount of ship's or, more important, shore labor and, where possible, bulk cargoes should be arranged to be self-trimming. There should be a constant relationship between the potential foot-tons stowed in a hold and the foot-tons-hour of lifting capacity available. This is an important point not always borne in mind in tramp ship design.

Two further aspects of basic design should be mentioned, namely, the ballast condition and the arrangement of accommodation. In the ballast condition the use of deep tanks is usually unavoidable and the ballast capacity should be adjusted so that a ratio of, say, 0.6 should be possible between ballast and load displacements and provision should be made, if possible, for limiting stability in this condition. If fitted, deep tanks should, in the author's opinion, be disposed always in a horizontal manner rather than in a vertical manner, as this enables clearer holds to be used and avoids small and inconvenient hatchways. In the forward part of the ship greater use should be made of deep double bottoms as the space occupied by these compartments is of relatively little practical value to the ship owner, anyway, while the stability can be reduced in the ballast condition by the use of tanks in the upper part of the ship.

EFFECT OF STRUCTURE TYPE AND INFLUENCE OF WELDING

There is very little to be said for adherence to out-of-date forms of construction in a ship of moderate size, such as a tramp ship. There are examples afloat which, while conservative in other ways, show excellent deadweight displacement ratios which are a reflection in the main of the adoption of modified tanker practice construction, combined with welding.

The practice of framing decks, double bottom and bottom shell longitudinally produces an undoubted economy in structure weight, while the valid objection to the use of stringers and longitudinal framing on the sides in the hold spaces is overcome by framing the sides transversely, as in tanker practice. Apart from the economy in steel weight, which is appreciable, framing a double-bottom structure longitudinally reduces the amount of overhead welding, and this lowers the cost per ton of such a structure.

An important effect on the deadweight displacement ratio is exercised by welded construction. In a ship of this type between 300 and 400 tons of steel may be saved by an

all-welded, as against an all-riveted, structure. Normal construction lies somewhere in between, but it would seem clear that in order to obtain high deadweight displacement ratios consideration should be given to as great an extent of welding as is possible.

Machine Effect.—Turning now to the effect of the type of machinery and its position upon the deadweight displacement ratio, a case is made later for pressure-charged (direct drive) Diesel machinery, and this, it is submitted, is best placed aft.

Approximately 100 tons of machinery weight can be saved by the adoption of pressure-charging, while the fuel consumption is slightly reduced. Also, by placing this machinery aft, a not inconsiderable weight of tunnel plating and of shafting itself can be saved. Summing up, a total of 200 tons of weight may be saved quite easily.

Accommodation Layout Effect.—The effect of the type of houses and their position is another aspect that should be considered. There are four possibilities, excluding specialized ships:—

(i) All houses amidships.
(ii) All houses aft.
(iii) Most houses amidships with a poop house.
(iv) Most houses aft with amidship navigation house.

Here, again, the choice must not be a hasty one. If the machinery is aft, all the houses must either be aft, or the main bulk of the houses aft with a navigation house just forward of amidships. The latter alternative is not a good one from the point of view of weight, and it is submitted that all houses aft or amidships, dependent upon the machinery position, are the economically sound choices.

Effect of Speed.—Finally, the effects of speed must be considered. Speed in a tramp ship is an increasingly necessary attribute, but where the ship is to carry deadweight cargoes the speed will have a noticeably adverse effect upon the deadweight displacement ratio, and, in fact, an extra half-knot may well lower the earning capacity of the ship if she is to be engaged on the carriage of deadweight cargoes as her main business. The lower speed and high block coefficient inherent in the early tramp ships helped them to overcome their heavy machinery weight and low structural efficiency.

It therefore must be underlined clearly to an owner that the competitive standing of his ship will be affected by what speed is chosen, although this is in no way a plea for lower speeds.

Finally, there is the question of gross and net deadweight. Too often, ships are quoted in terms of total deadweight. This is an accepted and long-established practice, especially in the shipping exchanges, but the author feels that it does not define the earning capacity of a ship. It would be more logical if ships were quoted in terms of cargo deadweight on a standard voyage of, say, 6,000 or 12,000 miles. Using a figure for total deadweight as a basis ofter penalizes the Diesel ship as compared to the steamship, especially in the higher powers where, in the past, direct Diesel drive has been compared with turbine machinery. Now the situation has changed somewhat with the successful introduction of pressure-charging, but, nevertheless, the total deadweight of a fast Diesel tramp ship and a fast steam tramp are usually comparable, whereas the cargo deadweights on a voyage basis are quite different and favor the Diesel ship.

If the latter is carrying a deadweight cargo, then a 10,000-ton 14-knot Diesel ship will be able to lift something of the order of 500-600 tons extra deadweight on a 12,000-mile journey.

It is clear that the use of pressure-charging will reduce the length of engine for a given horse-power, and with the new tonnage regulations advantage may be taken of this to increase the cargo cubic capacity without detriment to other features of the ship. This would appear to be a further reason for the adoption of this type of machinery in a modern tramp ship.

The cubic capacity is also affected by the position of the machinery and in a given case placing it aft may produce an increase in the capacity of about 2-3%.

BALLASTING

The ballasting arrangements have a definite, if secondary, effect upon cubic-capacity coefficient. The use of deep tanks in the average tramp ship is, in fact, detrimental to her useful cargo-carrying capacity as opposed to her actual cargo-carrying capacity, and this factor, of course, is affected by the position of machinery as well, as in both cases the owner has more usable space at his command the nearer it approaches to rectangular space and the easier the access to it. It is also unfortunate that access to deep tanks nearly always means a hindrance to the easy carrying of cargo in them when they are being used as cargo spaces.

As mentioned earlier, it is felt that ballast capacity in the form of deep tanks should be disposed horizontally rather than vertically as this means that hatches of the same size and area as the main-deck and weather-deck hatches can be incorporated and, in fact, the ship may become a three-deck ship in way of the ballast tanks. However, the very large free surface incurred is a disadvantage, and an alternative system is the use of tanks in the 'tween decks which, while incurring a certain loss of useful, as opposed to real, cubic capacity, are very much more easily disposed and do not involve the structural penalties and inconvenience imposed by deep tanks in lower holds.

Finally, the effects of speed and range are of fundamental importance, of course. The fast ship will, in general, have a good ratio of cubic capacity to net deadweight on account of her limited deadweight carrying capacity and relatively large internal volume, this volume being reduced less by the fineness of the underwater form than is the displacement, and hence the deadweight carrying capacity. One might expect, then, that a plot of cubic capacity against speed/length ratio would tend to reflect a smaller influence of speed upon this ratio than is the case with deadweight.

STRUCTURAL ARRANGEMENTS

The conclusion that the modern tramp ship may best be built with machinery aft introduces some difficulty in that in the load condition sagging moments are necessarily high compared with ships with machinery amidships, while in the hogging condition the stresses are generally lower. Ballasted, however, the tendency is the other way, and in the sagging condition relatively low bending moments will be experienced, while in the hogging condition the bending moments will be relatively much larger. The salient point here is that in the loaded sagging condition the compression stresses in the deck plating are like-

ly to be high in the ship with machinery aft, and this calls for additional resistance to panel buckling and hence, logically, to longitudinal stiffening of the decks with attendant advantages in structural weight and efficiency. The sides, however, are best framed transversely for the same reasons as tankers. The best method, therefore, would seem to be to construct the longitudinal structure with longitudinally framed horizontal surfaces and transversely framed vertical surfaces. Bulkheads could also be constructed of corrugated plating to considerable advantage as the saving in weight of a corrugated bulkhead, as opposed to a welded plate/stiffener assembly, is one that cannot be overlooked.

With an all-welded structure, the question of detail design and of local stresses arises, and it is not proposed to discuss here the subject of notch-sensitive steels with high transition points, as satisfactory practice in this respect is laid down by the Classification Societies. However, a great deal of trouble has occurred in the past at hatch corners and at similar structural discontinuities. Careful, and in many cases rather expensive, detail design can solve this trouble, as is, of course, general practice, but if possible it would be better to avoid the problem. In the ship with engines aft it is possible to do this with comparative ease.

If the longitudinal coamings of the hatches on the shelterdeck are run right through from one end of the cargo space to the other, and are integrated with bulkheads in the aft end of the ship and possibly in the forecastle, these coamings can be considered as part of the main hull girder and can be submitted to the Classification Societies as constituting such. Now, if between the hatches the deck is discontinued, and if the transverse coamings are then inserted and the area between the tops of the coamings is plated over, the deck is stepped and is not continuous transversely in way of the space between hatches.

This plating can be a good deal lighter than the plating of the deck itself and, in point of fact, considering longitudinal strain in the main strength deck, it is clear that there will be comparatively little tendency for the plating between the transverse coamings to accept any appreciable load due to shear lag in the longitudinal coamings, and in the plating between hatches themselves.

MACHINERY

For the tramp ship, contemporary practice would appear to favor the pressure-charged two-cycle engine, which is much the most compact single-acting plant, but there is reason to think that this should be of uniflow type to give high-temperature exhaust gases. If loop-scavenged, the resulting dilution by cold air lowers the ability to produce reasonably high-temperature steam. The four-stroke engine has been turbocharged to m.e.p. values of over 200 lb./sq. in., but this cannot be regarded as generally accepted practice, although examples are afloat in important installations. On grounds of size, simplicity and weight, as well as the considerations discussed above, the pressure-charged, two-stroke, single-acting engine, would appear to be the likely choice of the immediate future for the bulk of this class of tonnage.

For a ship with, say, 5,000 installed b.h.p., the following table gives representative relative values for the four types of machinery based upon 100-110 r.p.m. at the propeller and 240 r.p.m. on the geared engine.

TABLE 1

	(1)	(2)	(3)	(4)
Medium speed geared ...	1.25	0.37	0.39	115-130 (52-59)
Medium speed geared (pressure charged)	1.0	0.35	0.37	95-110 (43-50)
Direct drive Diesel	1.33	0.34	0.36	130-140 (59-63)
Direct drive Diesel (pressure charged) ..... (Two-stroke single-acting)	1.0	0.32	0.34	100-110 (45-50)

(1) The relative length of engine-room required.
(2) The specific fuel consumption lb./b.h.p.-hr. installed on Diesel fuel.
(3) The specific fuel consumption on heavy fuel (3,500 sec. Redwood).
(4) Representative weights of main engines only in lb./b.h.p. (kg./b.h.p.).

From the above table it is apparent that, for a ship which has to trade in the face of international competition, the pressure-charged two-stroke direct-drive Diesel is a most attractive choice. Table 2 gives approximate weights and volumes occupied of representative plants as chosen from these categories. Double-acting two-stroke engines are not common, but the recent change in machinery-space tonnage legislation may well bring a renewed interest despite their mechanical complication.

TABLE 2

Pressure-charged Main Engines Only 110 r.p.m.

Type	Lb. wt./b.h.p. (Kg./b.h.p.)	Approximate volume/ b.h.p. of total propelling spaces
2-stroke Single-acting .. Single piston .	100-110 (45-50)	12 cu. ft. (0.34 cu. m.)
2-stroke Single-acting .. Opposed piston .	110-120 (50-54)	15 cu. ft. (0.42 cu. m.)

Turning now to the question of pressure-charging, a moderate degree of pressure-charge would seem to offer nothing but advantage to the operator. Providing the b.m.e.p. is held below a figure of, say, 120 lb./sq. in., and bearings, etc., are suitably proportioned, the peak bearing loadings and peak explosion pressures and temperatures are all held to quite acceptable figures, while the mechanical efficiency is raised. Certain large engines use a separate exhaust-turbine compressor for each pair of cylinders, and this would seem to be a desirable practice.

MAINTENANCE OF TUREOCHARGED ENGINES

Maintenance costs for the blowers themselves are not an appreciable factor, being limited to blading inspection and bearing replacement at reasonable intervals. The machinery-aft layout particularly favors the single engine, as the shape of the ship allows a single engine to be accommodated much more readily than the wide gearbox of a twin-engine/single-shaft layout. If an engine of considerable length is used, however, the engine-room becomes rather long in a fine-lined ship, and here the pressure-charged engine offers a further advantage, enabling a much shorter engine-room to be used for a given power. The conventional tanker layout with a generator flat and/or exhaust-gas boiler flat in the after top corner of the engine-room is eminently suitable for the machinery-aft tramp ship and leads to an economical utilization of space in a portion of the ship which is not normally of much cargo-earning value. The use of pressure-charged machinery will lower the specific fuel consumption by about 0.02 lb./b.h.p.-hr., and the use of roller bearings for the propellor shaft in association with, if possible, loose couplings, of which several types are now

manufactured, will save possibly a further 0.005 lb./b.h.p.-hr. These savings cannot be ignored and again contribute to achieving the utmost economy. It would appear possible to achieve a fuel consumption of 0.34 lb./b.h.p.-hr. with such plant for all purposes, making full use of the exhaust steam.

FUEL

The use of heavy fuel in Diesel engines is now established practice and is of considerable importance, increasing considerably the economic lead of the Diesel ship.

If arbitrary figures are taken for an example, 5,000 s.h.p. on a 12,000-mile voyage, Table 3 gives a comparison of consumption for main engines only.

That figures such as these are not theoretical is borne out by owners' operating costs and by the widespread adoption of heavy oil up to 3,500 sec. Redwood viscosity for fuel for recently built and ordered tramp ships. Experience with liner wear appears to differ; some owners claim no increase in wear with heavy fuel, other equally well-authenticated sources state the wear is somewhat increased. However, with a single-acting two-stroke engine it is probable that this is not a critical feature, and this aspect of maintenance should not be given too much prominence. Here chromed liners would appear a significant factor.

TABLE 3

TYPE	Fuel	S.F.C. used	Assumed fuel cost/ton	Cost	Differential/ annum on 200 days/year steaming	Relative fuel cost/ton mile
Diesel	D.O.F.	0.32	£11	£6,500	+ £13,000	1.3
Diesel	Heavy	0.34	£8	£5,000	0	1
Turbine	Heavy	0.65	£8	£9,600	+ £31,000	2
Reciprocating with 1 reheat .	Heavy	0.85	£8	£12,500	+ £48,000	2.8

Navy oceanographers have set the record for underwater photography by photographing at a depth of 20,800 feet in the Sargasso Sea, about 1000 miles seaward of Cape Hatteras, N. C.

ENSIGN LAWRENCE J. FARRELL, USNR

MOTOR SHIPS FOR A STRONGER AND MORE SECURE AMERICAN MERCHANT MARINE

THE AUTHOR

was born in California and attended school there. In August, 1952, he entered the California Maritime Academy at Vallejo. Upon graduation in August, 1955, he received his ticket as Third Assistant Engineer, Steam and Motor Vessels, a Bachelor of Science degree and a commission as an Ensign in the U.S. Naval Reserve. He was called to active naval duty in September and began flight training to become a Naval Aviator. Ensign Farrell was awarded the Pi Sigma Phi key by the Propeller Club of America for this paper.

THE GREATER the nation, the greater must be its seapower. Because of our place of leadership in the free world, the United States must be able to provide a merchant fleet adequate to fulfill its responsibilities throughout the world. The United States is dependent on shipping for the importation of vital ores and raw materials. Only with our own ships can we be assured of access to these materials.

Eighty percent of the present day American Merchant Marine are war built vessels; of the 2000 ships in the reserve fleet, 1500 are of the next-to-useless Liberty class. All of these ships will soon be obsolete, probably within the next ten years. We have lost forty-eight large ships through casualties at sea since 1947. Our fleets have confined themselves to the operation of war built vessels, all designed as possible Naval auxiliaries, all of approximately the same size, and all constructed within a very few years. For the most part, these vessels are not of a type which can compete successfully in the foreign trade routes under private ownership without some form of government aid to enable them to meet foreign flag competitors with some degree of parity or equality. Meanwhile, other nations have embarked on extensive new building programs of fast modern ships, suited to particular voyages and cargoes.

In the 1850's our Clipper Ships almost ruled the trade routes, but we failed to stay in the lead due to improvements in steamships, and converted to steam only when our Merchant Marine was on the edge of non-existence. Today we are faced with a similar problem. It is necessary that we follow and surpass foreign nations that have outreached us in their building programs; but not with steam ships, as in the past. Following their lead, we must build motor ships designed for the trade in which they will be engaged.

As far back as September 30, 1938, Lloyd's Register of Shipping listed the total horsepower of marine heavy oil engines, either under construction or being installed aboard vessels, as nearly twice as great as the total horsepower of marine reciprocating steam engines and steam turbines combined. Today eighty percent of Scandinavia's merchant Fleet are motor ships, while ninety-three percent of new construction are motor ships. Other seagoing nations are closely following with their own figures. England at present has only two-thirds motor ships, but this is due to limited production rather than demand.

This widespread use of diesel propulsion outside of the United States has been made possible through higher power to weight ratios of modern equipment, brought about by such factors as welded steel frames, lightened reciprocating parts through the use of lighter weight alloys, and supercharged, two-cycle engines.

The auxiliaries of the main engines, such as pumps, only require approximately three percent of the total horsepower; a large improvement over the early marine units which required five to eight percent of the brake horsepower to drive the air compressor for fuel injection alone. The differences appear not only in the main engines, but in the auxiliary engines, cooling systems, and much of the miscellaneous auxiliary and accessory equipment that is now available. Dependable auxiliary engines of moderate speed, good balance, and modern design have contributed greatly to the success of the modern motor ship. The installation of units of sufficient capacity has greatly lessened the troubles formerly considered inherent in the auxiliaries.

Tugboats and small vessels will not longer consider anything except diesel power because of the lower first cost of propelling machinery and the almost double bunkering capacity required for the small steam installation. The small steam plant is inefficient because of the limitation of auxiliary machinery and the greater size and weight on a vessel where space and deadweight are very limited. An orderly program of maintenance carried out at annual overhaul and during port time will permit scheduling fleet operations up to as much as 7,500 or more hours per year for diesel propelled craft.

Progressive operators require a schedule imposing a minimum of eighty-five percent operating efficiency, a tribute to diesel reliability. Thus we see that the savings in diesel are not only in greater operation radius, lower fuel and personnel cost, but also in reliability; yet we have shown little use of it in our larger ships, seagoing or on the Great Lakes. The present figures show that only eight percent of vessels under the American flag are motor ships, and many of our best war produced motor ships were sold to foreign operators at bargain prices. Modern marine diesels are not limited in power for anything except the largest and fastest passenger ships. Single units are now available up to 12,000 shaft horsepower, and units are easily coupled into any desired propulsion size.

When the diesel engine is used in place of turbo-electric, geared turbine, or reciprocating engines the saving in fuel consumption and the increase in net tonnage is high. This is due to a smaller main engine which requires less fuel to be bunkered for the same cruising radius. The amount of fuel used in an oil-fired ship is at least fifty percent more than that used in a corresponding motor ship, and with a greatly reduced fresh water reserve. Consequently, with the same bunkering capacity, the purchase of fuel can be made at the ports of call where it is the cheapest. Due to increased cruising radius over steam ships, when cargo is not plentiful (as is the case today) this might easily mean the difference between loss and profit!

The machinery installation of a steam plant includes boilers, auxiliary machinery, and the main propulsion unit. As such, the space occupied will be greater than that required for a diesel installation, which has no boilers for main propulsion, and a great deal less auxiliary equipment. This is of considerable importance for ships that are designed for the purpose of making very long voyages. The steam installation cuts down net tonnage, hence raising the cost per ton of cargo. Even the small C-1A shows a cargo carrying increase of 380 tons with diesel propulsion.

In a comparison of motor and steam turbine vessels in the C-1A class operated by the Mississippi Shipping Company, the cost per mile of fuel for the steam ship was $1.318, burning bunker "C" at $2.51 per barrel, as against $1.154 per mile on the 4000 shaft horsepower motor ships burning fuel at $3.40 per barrel. The in port cost of fuel for the steam ship was $2.885 per hour, as against $1.241 per hour on the motor ships. Though the engineering personnel of a motor ship demand premium base pay, there are less operating personnel due to the absence of main boilers, and the company cites a saving of $259.53 a month on the base pay for the motor ships, and savings of slightly more than $10 a day in overtime. In addition to the payroll difference, it may be pointed out that without the three firemen of the steam ship, there is approximately a $180 per month saving in subsistence costs.

The average daily cost of maintenance and repairs chargable to the engine department on the motor ships was $40, while on the steam ships the average was $48 per day. Including fuel costs, lube oil, engineering personnel, and maintenance and repairs the motor ships have shown a yearly saving of $25,605.72 over operation of the steam vessel. Since the time of these figures the motor ships have had a propeller conversion that has cut fuel consumption 0.02 barrels per mile, saving an additional $4020 per year, and a lube oil conversion to waste-type filter elements that shows a saving of $1390 per year. Altogether the saving is $31,015 per year in favor of the motor ships. Because of the aforementioned figures the Mississippi Shipping Company is planning a luxury-type passenger liner of 23,000 tons displacement, to be powered by diesel.

A C-1A operated by the Moore-McCormack Line has traveled a distance equal to eleven times around the world without any trouble or delay. In comparison with the C-1B steamships operated by the same company, the motor ship has shown a larger cruising radius, the same maintenance costs as the steam ships, and a port fuel consumption of only 9 barrels per day, as against 32 barrels per day on the steam installation. This is a saving of $8,000 in annual port fuel costs alone.

The *Vacationland,* world's largest double ended ferry, of the Michigan State Ferry Service, showed a yearly saving in fuel costs of $38,477 over that company's fastest steam ferry. This vessel has 9300 shaft horsepower, almost four times the power of the steam ferry, and made 1500 more crossings, operating for eighty-eight more days during the year, with fifty percent more vehicle capacity!

The average world price of fuel today is $28 per ton of diesel oil and $21.60 per ton for boiler fuel. A 15 knot cargo vessel of 9000 dead-weight tons,

fully loaded, with 6000 shaft horsepower, will have an overall consumption of 24 tons per day of diesel oil while at sea and 2 tons per day while in port. The same ship with geared turbine will burn 38 tons of fuel per day while at sea, and 6 tons per day while in port. A vessel today very often spends half of its time in port, and under these conditions the yearly fuel cost for the motor ship will be $133,000, as compared to $163,000 for the steam turbine, or a saving of $30,000 per year in fuel costs to the ship with diesel propulsion.

The cost of converting a 4000 indicated horsepower diesel unit to burn oils in the boiler fuel range is approximately $20,000, for special fuel purifying equipment and the few engine alterations. The annual saving in the fuel cost will run about $40,000 while showing little, if any, increase in repair or maintenance costs over those for vessels burning the lighter grades of oil. Thus the conversion should pay for itself in the first six months of operation.

Three motor propelled super tankers, built in 1951 and operating on boiler fuel, have shown only two thirds the daily consumption of similar steam ships, or a saving of one third of the fuel bill. Liberty ships repowered with 3600 shaft horsepower diesels, using boiler fuel, have shown a speed of 12.4 knots, as against the original 10.3 knots when powered with steam reciprocating engines of 2500 shaft horsepower. The daily fuel consumption of these vessels is only 105 barrels, where the former installation used 168 barrels of fuel per day.

On the Great Lakes, because of required reboilering due to long hull life, many operators repower with diesel. The cost of reboilering is approximately $750,000, and repowering with modernized diesel installations costs $1,100,000 to $2,000,000. The slow speed diesels which burn industrial grade fuel are saving $25,000 annually in fuel costs alone.

The diesel has a high economy in the use of fuel over a wide range of speed, and thus is ideally suited for the varying conditions of load and speed in ship operation. Conversely, the steam turbine falls off in efficiency greatly above its designed cruising speed, and falls off drastically below this speed. Under normal operating conditions the modern diesel propulsion plant should operate with a consumption of only 0.4 pounds or less of fuel per shaft horsepower hour, for all purposes, while the steam installation will burn 0.55 pounds or more per shaft horsepower hour.

The diesel engine is today the most efficient means of converting fuel energy into mechanical power. Modern marine diesel installations are of the slow or medium speed type. Reversing couplings are used on small units in the tug class. These units use heavy fuel oil in the boiler fuel range, or gas oils in the two cycle single acting or opposed piston type engines. The double acting engine is not often found today due to less reliability, and the greater ease of overhaul and maintenance of the single acting units; nor is the four cycle engine often used due to its lower power to weight ratio.

The use of direct connection saves the fourteen percent loss in the brake horsepower of the turbine to the shaft of turbo-electric drive, and the five to three percent loss in the gearing of double reduction geared turbine drive. This machinery arrangement has the advantage of the elimination of the cost, weight, and maintenance associated with geared reductions and electric motor drives. Even the single reduction geared diesel only shows approximately half the loss of the usual double reduction of geared turbines, while giving great flexibility of operation; approximately the same loss is found in the hydraulic or electro-magnetic couplings as for single reduction. Thus the brake horsepower of the diesel is fully delivered to the shaft, reducing the cost per mile of operation. In addition, the choice of a heavy duty, slow speed engine contributes to continuous uninterrupted service.

On a motor ship the fuel economy, when she is ready to be retired, is practically the same as that obtained on her trial runs. This was shown by the Sun Oil Company's figures after sixteen years of operation; for the *Selandia*, built in 1912, after twenty years of operation the daily fuel consumption was slightly lower than at the time of putting to sea. This performance is impossible to duplicate in a steam ship.

An important operating characteristic of diesel engines in marine work is their high accessibility. Maintenance inspections and overhauls can be carried out between voyages and while the ship is in drydock. It is unnecessary to lose valuable operating time for such work. On two ships of the Delta Line, powered with diesel, on their first survey; one inspection was conducted during idle status by a group of relief engineering personnel at a wage cost of $1,600 and a parts replacement of $600. The other survey was conducted during regular port time, the only cost being the usual American Bureau of Shipping fees. And this was after four years of operation!

The Tide Water Associated Oil Company, which operates the diesel tanker MS *Tydol Flying A*, has found this vessel so reliable since putting it in operation in 1948 that no allowance is made for machinery breakdowns when scheduling operations.

Our marine diesels are among the finest in the world, and many of them are used on foreign motor ships. Ship repair companies state that less man hours are required to repair an American diesel than the average foreign make of the same size and horsepower.

The engines will last as long as the ship, and obsolescence and interest charges can be determined accordingly. Although diesel installations are slightly higher in this country on ships requiring over 2500 shaft horsepower (they are cheaper abroad through widespread use, than steam) their usefulness for the life of the vessel easily makes up for the slightly higher first clost on seagoing ships. This higher initial cost is approximately $350,000 maximum for 10,000 shaft horsepower vessels.

It has been shown that in these days of small, or

no profits, the use of motor ships may easily make the difference between black and red in the company's reports. The motor ship can carry more cargo and have a larger cruising radius than the steam ship, thus fueling at cheaper ports; the cost per mile for fuel, repairs, and maintenance are a great deal lower, and wages and subsistence for the engineering personnel are less. The modern motor ship has proven its advantages; it only remains for American flag operators to realize this, and follow the lead of other seagoing nations to a stronger and more secure American Merchant Marine.

BIBLIOGRAPHY

Anderson, J. W., *Diesel Engines*, McGraw-Hill Book Company Inc., New York, 1940.

Anonymous, "Ferry Tale That's True," *Motorship*, March, 1954.

————, "Repowered Tug Sets Service Record," *Nautical Gazette*, October, 1951.

————, "The Vacationland Will Increase Michigan State Ferry Service 30 Percent," *Marine Engineering and Shipping Review*, April, 1952.

Boyle, Charles L., "Diesels in Ocean-Going Tankers," *Proceedings American Merchant Marine Conferences*, 1948.

Chalkey, A. P., "European Motor Ship Development," *Proceedings American Merchant Marine Conferences*, 1948.

Christensen, Paul A., "Diesel Engines in European Cargo Vessels," *Proceedings American Merchant Marine Conferences*, 1950.

Diesel Engine Manufacturer's Association, *Marine Diesel Engine Standards*, '40.

Dawson, A. J., "Diesel Engines in River Traffic," *Proceedings American Merchant Marine Conferences*, 1949.

Downer, Hugh C., "Interesting Aspects of Repowering Lake Vessels," *Proceedings American Merchant Marine Conferences*, 1953.

Earle, J. G., "Engine Performance In Modern Motorships," *Nautical Gazette*, November, 1950.

————, "Means of Securing Top Performance From Diesel Engines in Off-Shore Service," *Proceedings American Merchant Marine Conferences*, 1951.

Eitram, Captain Wilhelm, "Diesel Operating Experience," *Proceedings American Merchant Marine Conferences*, 1949.

Ford, Louis R., *Marine Diesel Handbook*, Diesel Publications Inc., New York, '44.

Friend, Robert E., "Diesel Engines in Cargo Vessels During The War," *Proceedings American Merchant Marine Conferences*, 1948.

Heldt, P. M., *High Speed Diesel Engines*, P. M. Heldt Publications, Nyack, New York, 1947.

Kelly, Richmond K., "Diesel Engines in Tankers," *Proceedings American Merchant Marine Conferences*, 1950.

King, Reno C., *Practical Marine Engineering*, Prentice-Hall Inc., N.Y., 1952.

Lecourt, Stanley M., "Diesel Engines in Ocean Cargo Ships," *Proceedings American Merchant Marine Conferences*, 1949.

————, "Economical Development on the C-1 Diesel Cargo Ships," *Proceedings American Merchant Marine Conferences*, 1950.

Lienhard, George, "Recent Diesel Engine Developments and Their Application to the Marine Industry," *Proceedings American Merchant Marine Conferences*, 1952.

Pate, Louis B., "We Must Have an Adequate and Balanced Merchant Marine," *Proceedings American Merchant Marine Conferences*, 1949.

Potter, Hon. Charles E., "We Cannot Afford Not to Have an American Merchant Marine," *Proceedings American Merchant Marine Conferences*, 1953.

Training, Bureau of Naval Personnel, *Fundamentals of Diesel Engines*, Government Printing Office, Washington, D.C., February, 1951.

Saltonstall, Hon. Leverett A., "A Progressive Maritime Policy," *Proceedings American Merchant Marine Conferences*, 1952.

Sanford, Leigh R., "The Outlook for Ocean Shipbuilding," *Proceedings American Merchant Marine Conferences*, 1953.

CAPTAIN R. E. W. HARRISON, USNR, RETIRED

VIBRATION (AID TO THE ENEMY AND A COSTLY NUISANCE AT HOME)

THE AUTHOR

was born in Manchester, England, in 1893. Educated Manchester College of Technology. With Royal Engineers, British Army 1914–1919, Egypt, Gallipoli, Sinai, France, Belgium. Industrial Engineering experience includes special apprenticeship and supervisory positions with Churchill Machine Tool Company, England, in the building, design and engineering selling of precision grinding machinery; in 1926 as Director of Engineering, Cincinnati Grinders, Cincinnati Milling Machine Company; 1934 Chief, Machinery Division, U.S. Department of Commerce; 1935 Vice-President Chambersburg Engineering Company; in War II, on staff of Assistant Secretary, U.S. Navy, and later as Special Assistant to the Under-Secretary; Registered Mechanical Engineer in Ohio, New York, Pennsylvania, Maryland and District of Columbia. Fellow ASME and Royal Society of Arts; Member other Engineering Societies in USA and Europe. At present engaged in Engineering and Management Consulting, Washington, D.C.

In most branches of those industries, based on mechanical engineering concepts, it took much repetition of sad experiences to prove to the operators that perfection is unattainable and the best that could be done was to put high and low limits of permissible departure from true accuracy on all important dimensions.

As machine tool performances were improved, the costs of accuracy entailed by close tolerances decreased proportionately, and as demonstrated in today's mass markets for domestic machinery, we can buy mechanical equipment with dimensional tolerances as low as plus or minus .0005" for a price which includes a relatively small percentage cost component for skilled labor. A U.S. nationally accepted scheme of fits and tolerances for cylindrical parts and limit gages has been in use for many years.

Concurrent with the improvement in dimensional control, there came the demand for quality of finish on work-loaded parts subject to expensive wear, which would protect the investment in accuracy, by limiting the initial wear, and the subsequent rate of decline in accuracy. This demand led to the setting up of another U. S. Standard.

There now emerges urgent need for a related and additional Standard to protect both investments in accuracy and finish of machinery—this being a Standard of limit to permissible vibration or shake.

Evolutionary manufacturing progress demanded dimensional control, as a basic requirement to interchangeability and correct functional fit—the same force demanded finish control wherewith to make dimensional control meaningful—and now—this same economic pressure, which usually motivates most evolutionary progress, demands a rationalized set of limits on maximum permissible vibration.

Vibration in fine machinery is now, as always, its greatest destroying element reducing its economic life—and eventually invalidating the system. The structure borne noise this vibration generates, while a prime nuisance in domestic machinery, is, in military machinery, often a fatal menace.

So—just as requirement (1) brought forth the micrometer—and requirement (2) gave birth to the

profilometer—so, requirement (3) has fathered the Vibratron, an instrument which portrays at a glance the amplitude and frequency of the dominant vibration in any system of mechanisms.

History often repeats itself in a logical way. The needed instrument of measurement, or calibration, precedes the establishment of a servicable National Standard.

From the Naval Engineer's viewpoint, there is a great deal of merit in the proposed establishment of a system on National lines, whereby we could buy and operate machinery specified in terms of maximum amplitude and frequency of vibration under all loadings.

Super-sensitive hydrophones have rendered, for all time, obsolete the crude methods and instruments of former years, especially the mechanic with the allegedly calibrated fingertips—structure borne noise, having its birth in vibration, has assumed the proportions of a deadly menace in the current day of accoustically directed torpedoes, and there is left to those who know whereof that about which they speak, not even the shadow of a doubt, that the presence of a discernable vibration aboard a submarine can and will write Kaput! to seventy-five priceless lives and a $30-million piece of machinery.

In a shore installation, we can, as occasion demands, shut down the plant for repairs, when machinery vibrations get to the danger stage—switch the electrical load onto the grid—or send the workmen home—or have them clean the factory windows; but at sea, in a fighting submarine, deeply submerged, with enemy warships on the surface nosing around for a clue, there are but few things a crew can do —keep quiet and pray, being the two most obvious.

There always exists an urgent need to get at the root of the noise emission trouble, and that need starts in the plant of the manufacturer who makes the machinery on contract. A good and workable system of maximum permissible vibration amplitudes shown on drawings and specs, along with quality of fit and finish properly specified will give an inspection crew all of that which is needed to accept or reject the equipment offered.

However, that is far from being the end of the story in submarine operation, as even assuming that we have all twenty items of essential operating machinery within acceptable tolerances of vibration amplitude, there being no such Utopian thing as perfection in this world, we will still be confronted with other problems stemming from harmonics, and that means mandatory installation of all available precautionary insulation mechanisms which space and the traffic will bear.

A relatively new ability to accurately probe for, find and gage sources of vibration aboard ship eases this phase of the problem—but will *never* eliminate it, i.e., the problem will always be with us and only by eternal vigilance can it be kept under control to the minimum requisite for safety of crew and ship.

What is required is a permanently installed noise monitoring system.

Having regard to the vital need to suppress noise emission when a submarine is in "patrol quiet" status—there has been proposed the installation of a permanently installed machinery vibration monitoring system which will instantly telegraph to a control station, readings from a score or more of sensitive spots where trouble could originate.

Such a monitoring system with sensitive pickups at key points of potential trouble would be continuously scanned throughout the anticipated frequency range or spectrum, and a defective bearing—a hammering pipe hanger—a concentration of water hammer in the hydraulic system—even a loosened foundation bolt, or an imbalance in an overheated rotor—could be detected and corrected before the offending piece of machinery had transmitted its macabre invitation to an enemy.

A similar valuable service could well be provided in monitoring potential trouble spots in powerhouse machinery ashore. In this case the manipulation of a selector switch on the main board can be made to tell the shift engineer, where, if anywhere, excessive vibration had developed, and if it had assumed serious proportions calling for prompt corrective action.

It is usual for tests of similar nature to be run on test airplanes in flight—but only on an experimental exploratory basis. However, the sponsors of these tests have not been slow to affirm that the resulting data are of immense value to those concerned with the problems of design, maintenance and satisfactory operation.

The need for a good standard, setting forth acceptable tolerances of permissible vibration, has not gone unnoticed in the past, and no body of men has been more alert to the implications than the larger insurance companies, who pay the bill when large pieces of insured mechanical/electrical machinery blow up.

The key to this interest is provided by evidence in subsequent enquiry into the disaster, which all too frequently records that there was a perceptably growing, but unheeded vibration, in the piece of machinery which eventually failed.

By permission of the Editor of Power Plant Engineering, and the author, the following excerpt from a paper by T. C. Rathbone, Chief Engineer, Turbine and Machinery Division, The Fidelity & Casualty Company of New York, is quoted, as evidence of the analytical approach which has been found desirable by a farsighted and extremely competent plant insurance company.

Last efforts to establish a relationship between allowable vibration amplitudes on machines based on their operating speeds have generally been founded on faulty premises. For example, it has been assumed that the intensity or seriousness of vibration depends on the acceleration of the motion rather than directly on the amplitude. Thus, the force with which a rider is "thrown backward" in a car depends on how quickly the car is accelerated from say, zero to ten miles an hour, rather than on the distance traversed.

With simple harmonic motion, like that of the crosshead of an engine with an infinitely long connecting rod,

the acceleration varies not directly with the amplitude, but with the square of the frequency or the speed causing the vibratory disturbance. Thus, for two equal vibration amplitudes, one at twice the frequency of the other, the acceleration of one is the square of two, or four times the other.

This fact, together with the questioned assumption that the deleterious effect is in direct proportion to the acceleration, has given rise to the so-called "inverse square" rule in attempting to establish vibration tolerances for various speeds. By this rule, if an amplitude of 0.002 in. is permissible for an 1800 rpm machine, then 0.008 in. would be allowed at 900 rpm but only 0.0005 in. at 3600 rpm. Such a rule is inconsistent with experience and cannot be applied generally for there are also other factors which prevent rigid comparative values.

Vibration classification may be affected according to the purpose of the criteria. For example, the manufacturer and the purchaser of new equipment are interested in whether the operation comes within what has been vaguely termed "commercial balance," while the insurance underwriter is more vitally concerned with the extent of vibration allowable before the operation becomes hazardous. In this paper, Vibration in its relation to possible damage will be the major consideration in attempting to establish tolerances.

Often the problem is concerned more particularly with higher speed machines, such as steam turbine generators and their running balance, but there is no reason why it should be so confined. Professor G. B. Karelitz of Columbia University, while associated with the author on vibration studies at the Westinghouse South Philadelphia Works, tabulated the opinions of several practical engineers and inspectors as to the smoothness or roughness of a number of turbines while on test, operating mostly at 1800 rpm, and correlated this data with simultaneous vibration records made with the vibrometer. To this has been added considerable data obtained by the author and his present associates in their machinery inspection activities on all classes of apparatus. The whole has been digested and averaged to arrive at a tabulation of amplitudes in the various categories of smooth, fair, rough, and dangerous, etc., throughout a wide speed range. The resulting data is used by the turbine engineers of the Fidelity & Casualty Co. merely as a guide in their inspection activities.

Measuring Instruments: Instruments for measuring machinery vibration are now fairly common. They are generally of the seismometer type, and customarily are applied at the bearings. The majority of vibrometers measure one component of the motion, such as the vertical, lateral (transverse) or axial (longitudinal). The Davey photographic vibrometer indicates and records the actual path of vibratory motion in a vertical plane, either transverse or axial, so that both vertical and horizontal components are directly observed as the shape or path of the resultant motion. Electric type vibrometers indicate vibration velocity, calibrated in terms of amplitude for given speeds.

If the vibration is simple harmonic at a common frequency, the figure is some form of the ellipse. The figures are often distorted, however, by the presence of two or more frequencies, or by impactive forces such as pounding at the bearing keys, loose wheels, coupling or gear disturbances, etc. A common figure due usually to impact resembles a mutton chop. Acceleration is no longer proportional to displacement with such distorted motion. This is why two vibrations with the same amplitude and frequency may "feel" quite different, one smooth, the other hard or sharp.

In estimating the severity of a vibration it is thus important to know its character, to make due allowance for any abnormal condition or deviation from simple harmonic motion. The tolerance for one component may not agree with that permissible for the component in another direction. For example, 2 mils of vertical amplitude may create a much greater general disturbance to the unit as a whole than double that amount in the lateral direction. In fact, such a condition is the rule rather than the exception.

Individual bearings often require separate consideration. On the larger condensing turbine-generator sets with massive and rigid supporting of the No. 2 bearing, an amplitude of say 3 mils vertical would generally represent a far more severe disturbance to the unit as a whole than an equivalent amplitude at the thrust or outboard bearing. Thus a more stringent tolerance would be in order at this location.

Outboard bearing pedestals are usually independent members and their vibration is more or less localized. It is not uncommon to find amplitudes as great as 3 or 4 mils at 1800 rpm in the lateral and particularly the axial direction, with little disturbance to the main unit. Thus, a greater tolerance may often be permissible for this bearing.

Amplitude Alone Meaningless: The statement that the vibration at a bearing has a certain amplitude may be meaningless, unless the location of the vibrometer is definitely specified and comparative readings always referred to that location. Almost invariably the amplitudes observed simultaneously at the two sides of the bearing show some difference, and sometimes the amplitude at one side may be double or more the other. The amplitude at the top center of the bearing pedestal cap is generally greater than at the horizontal joint flanges, particularly in the lateral and axial direction. This condition is due to a common rotary or conical mode of vibration about a node located at one side of the base of the pedestal. Such a mode of vibration can readily be explored by means of the small hand type vibrometers, and should always be ascertained if the vibration is appreciable. It is recommended that all bearing vibration be observed at a definite location, such as the top of the pedestal cap.

Resonance characteristics of the structure as a whole may operate to allow increased tolerances, particularly if the bodily movement of the rotating and stationary parts are in unison. It is now understood that the amplitude of vibration for a given unit of unbalance at a given speed is largely a matter of accident, as it depends on the amplification factor, which is fixed by the relation between the operating speed and the resonant speeds of the several modes of vibration.

It is not yet possible to control or predetermine these resonance characteristics with any degree of certainty. Although turbine generator units may be identically constructed, the foundations, which play such an important role in determining the resonance characteristics, vary greatly. A pound of unbalance at the balance hole radius may cause a vibration of 10 mils on one unit, but only 2 mils on another unit at the same speed. Thus, to reduce the amplitude on the first unit, extreme refinement in balancing is necessary, due to the much greater sensitivity of response. Obviously, the destructiveness cannot be in proportion, as the centrifugal forces responsible for the disturbances are roughly the same for relatively rigid rotors.

Resonance Curves: Allowance may properly be made in applying tolerances with such a situation, if a large amplification factor at the operating speed is demonstrated by actual resonance tests. Such a test merely involves the determination of amplitudes corresponding to various speeds, preferably up to 10 percent overspeed. The plotted results are called resonance curves and represent the inherent characteristics of the installation.

These facts indicate that a better criterion might be based on the amount of residual unbalance rather than on the resulting amplitude. With the more modern field balancing apparatus now available which determines the phase as well as the amplitude of vibration, the residual unbalance is readily determined by the unit vector process. When unusual sensitivity is encountered, the residual unbalance information actually should be recognized in establishing a tolerance.

Resonance or great sensitivity for small unbalance cannot, of course, serve to condone a vibration which is palpably hazardous to the unit. Resonance of individual parts and appendages, such as the steam lines, governor dome, valve chest, etc., unless corrected by structural alterations, may require more stringent tolerances than the bearing vibration.

The general mode of vibration of the installation at the operating speed may result in a node or dead point occurring near one or more bearings. In such a case, the general disturbance of the unit as a whole may be out of all proportion to the amplitudes observed at the bearings, and individual treatment again becomes necessary. The vibration or jumping of the shaft itself, apart from the bearing vibration, may aid in estimating the condition of the unit, if the reference location on the shaft is known to be smooth and concentric with the journals. Where the general vibration is great but the bearing vibration is small, the shaft motion itself may disclose an unsatisfactory condition, but large bearing vibration may exist with little relative motion between the bearing and shaft.

In estimating the general disturbance to the unit as a whole, the experienced observer will not be deceived by the clatter and chatter sometimes set up by loose floor plates, hand rails and the like, which may occur even with a smooth running unit. He is concerned however, with the vibration of the piping, linkages, governor and other appendages, the general vibration throughout the entire structure and surroundings, and the noises heard in the bearings and cylinder parts with the listening stick.

Danger Point: The magnitude of vibration that is almost certain to cause damage is of course problematical. One important factor is the closeness of the clearance between the stationary and rotating parts, and whether the rotor vibration is in or out of phase with the movement of the stationary parts. The possibility of great shaft deformations as a result of rubbing contact is important. The author once witnessed a vibration at the No. 1 bearing of a large 1800 rpm turbine which reached a momentary value of 30 mils, with no ensuing damage. This is exceptional, as blading and packing rubs causing damage have occurred with vibration less than 8 or 10 mils, at this speed. Continued large vibration is, of course, more serious than momentary peaks such as occur with sudden load changes, as fatigue of parts or bearing damage may ensue.

It is evident from what has been said, that each installation requires individual consideration, based on experienced judgment.

The graphs of vibration do not follow the inverse square of frequency law, or any other fixed index, particularly at the lower ranges. If we held to this law and extrapolated to low frequencies, we would soon reach a situation where an allowable amplitude would be great enough to disrupt the parts. For example, assuming the inverse frequency squared rule, if 2 mils can be allowed at 1800 rpm, then the tolerance would be 8 mils at 900, 32 mils at 450, 128 mils at 225, and 512 mils—over half an inch, on a 112 rpm engine. This is obviously unthinkable. For low speed reciprocating machinery, with its unavoidable residual external reactions, it is common engineering practice to design the base with sufficient mass to limit the maximum rocking to a definite amount, such as 5 mils.

Also the graphs in the frequency range from 600 to 3600 rpm roughly follow the slope of the proposed threshold and nuisance graphs for comfort in buildings, which were arrived at independently from physiological considerations. But below 600 rpm or 10 per second frequency, the machinery tolerance graphs curve downward to smaller values, crossing the physiological graphs. This is reasonable, as the sensory perception of low frequency vibration bears no relation to the stresses set up by the movement. Experience beyond 5000 rpm is somewhat meager, but the slopes extrapolated with the index $af^{1.7}$ appear to be reasonable and consistent.

Summarizing, the chart values characterizing the severity of machinery vibration represent the results of a great number of observations on many types of machines, and are based on practical rather than on theoretical data conforming to some assumed relationship. Variations of 25 percent or more either way are to be expected in individual cases. With proper recognition of the various influencing factors described, a chart should furnish a reasonable guide for estimating the severity of vibration."

The essence of this article is advocacy of planning for the principle of continuous vibration monitoring on both seagoing and land-based machinery—designed not only as a tool of preventive maintenance, but also as the best form of insurance against disclosure of the presence of U.S. fighting ships to an actual or potential enemy.

Monitoring—automatic, visual or aural—is of the very essence of today's technique for keeping complicated and expensive plants in satisfactory operation—and the addition of a vibration control panel to those already in accepted use, adds a needed safeguard to a system which, otherwise, is extremely vulnerable to sudden and fatal disaster.

GEORGE UBERTI

MEASURING GEAR TOOTH WEAR

THE AUTHOR

was born June 9, 1923 in Philadelphia, Pennsylvania and was graduated from the U.S. Merchant Marine Academy in June 1948. After service on merchant vessels, he became employed at the Naval Boiler and Turbine Laboratory from 1950 to present. He attended Massachusetts Institute of Technology under a scholarship from the Society of Naval Architects and Marine Engineers, receiving a degree of Master of Science in 1954. He holds associate membership in the S.N.A.M.E. and in the Society of Sigma Xi.

INTRODUCTION

GREATER hardness and improved finish of teeth are important items in modern reduction gear development. Their successful attainment will permit stress increase or size reduction for given powers. Both are requisite in conforming to demands for minimum space and weight without sacrifice in reliability.

To that end extensive tests of both conventional and advanced types of ship main reduction gears are conducted at the U. S. Naval Boiler and Turbine Laboratory,† each step in that testing being followed by thorough examination of pertinent gear parts.

After the gears have been subjected to individual runs, which collectively form series covering wide operating ranges with particular emphasis of full power and overload, the elements are disassembled and transported to a room wherein temperature is carefully controlled. Inspections conducted there enable the influences of special gear properties definitely to be established as alternate operation and examination proceed.

GEAR MEASUREMENTS

The quantities measured in the gear inspection room are principally geometric.‡ They include accurate determinations of tooth involute profile and helix angle, tooth spacing, circular and normal pitch. Standard commercial measuring machines are employed with most sizes of main propulsion gears. The information produced by those machines is illustrated in figures 1, 2, and 3. The involute profile checker shows deviations from a true involute generated by the machine (figure 1). The error is plotted from tip to root as a pointer traverses the profile. Similarly, the gear lead checking machine produces a curve of deviation from the correct helix angle generated by the machine at the tooth pitch line (or at any other depth) as the pointer travels along the tooth length (figure 2). Tooth spacing, circular and normal pitch dimensions are illustrated in figure 3.

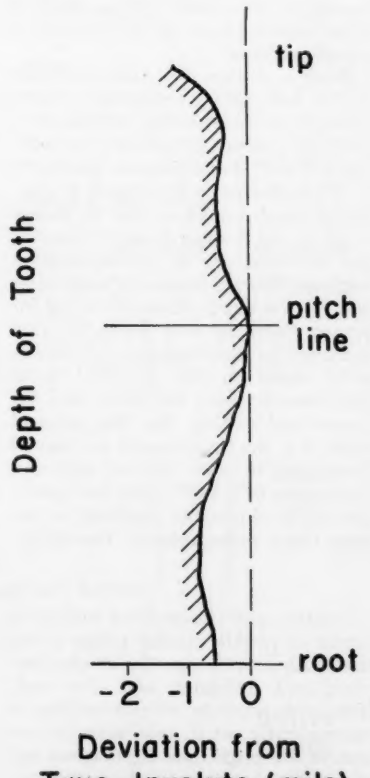

Figure 1. Typical tooth profile check. (Verticle dash line represents true involute.)

† "Marine Propulsion Gear Testing at the Naval Boiler and Turbine Laboratory," by CDR Ivan Monk, USN, Trans. of the A.S.M.E., Vol. 71, July 1945, pp. 487–489.

‡ "Gear Measuring Equipment Used by the Bureau of Ships, U.S. Navy," by John W. Sawyer, Journal of the A.S.N.E., Inc., Vol. 64, No. 4, Nov. 1952, pp. 719–731.

TOOTH WEAR

Tooth wear, or difference in thickness before and after operation, has been an elusive quantity to measure. Though unapparent, dimensions shown in figure 3 fail to yield that information. Were actual lengths of "a" and "b" known, it would be simple to obtain tooth thickness by subtraction, but the dimensions of figures 1, 2, and 3 are relative from tooth to tooth or to an arbitrarily located reference line. The machines, therefore, show *variation* in pitch and spacing from tooth to tooth and *deviation* from a theoretically perfect involute and a correct helix angle. (The importance of these measurements are not to be minimized because they are only relative. Good operation requires uniform pitch and spacing from tooth to tooth, accurate profiles and helix angles.)

Present practices of direct tooth thickness measurement are insufficiently accurate for showing wear. The gear tooth vernier caliper indicates thickness at a set tooth depth in units of 0.001″. The accuracy of machines used in the gear room to show wear effect is 0.0001″ or better; therefore, to measure wear itself, it is necessary to use an instrument of equal precision.

Such a device, designed and built at the Laboratory, comprises essentially three micrometers arranged to position a measuring finger contacting a 0.0001″ dial indicator. See figure 4. While the pitch line depth is generally used, thickness can be measured at any desired depth by turning the micrometers to predetermined settings. A wide range of tooth sizes can be measured. After adjusting for proper thickness and depth, the dial is zeroed by inserting gage blocks exactly equal to the specified tooth thickness between the finger and the frame and setting the dial to read zero. As the instrument is moved from tooth to tooth, the dial will read deviations in 0.0001″ from the specified tooth thickness. Applied to the gage block measurement, the deviation gives an absolute value of tooth thickness at the pitch line.

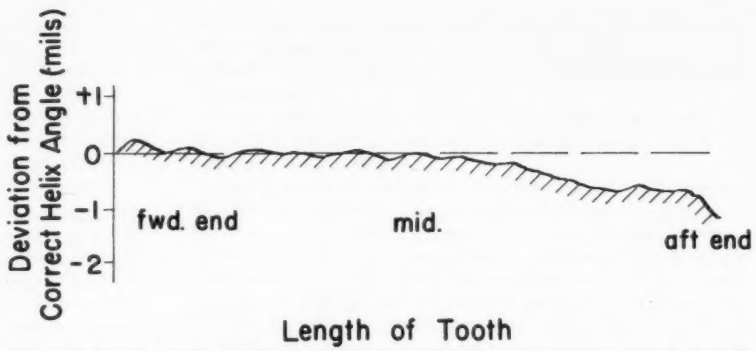

Figure 2. Typical helix angle check. (Horizontal dash lines represents correct helix angle.)

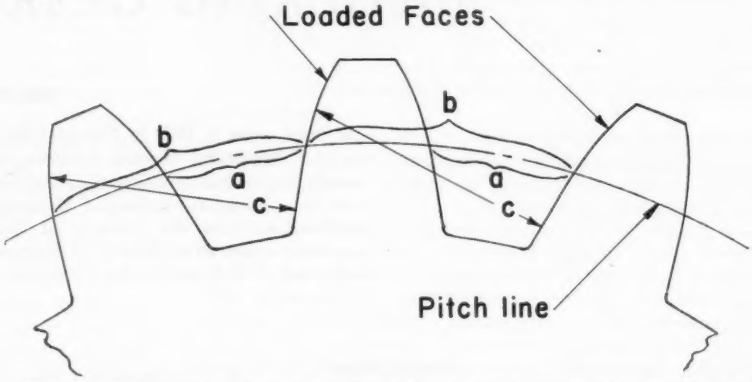

Figure 3. Pitch and spacing measurements. (a. tooth spacing; b. circular pitch; c. normal pitch.)

Influences of gear misalignment, load concentration, end thrust, geometric inaccuracies and the like are often manifested in tooth wear. Knowledge of the wear all over the surface is desirable for a study of gear attrition progressively as load is increased. Obviously, use of the tooth thickness measuring instrument at many points on the surface is a cumbersome task. A glance at figure 4 shows that measurements at the tooth ends, where wear has somewhat greater significance, cannot be taken with this instrument—for the frame would ride off the tooth.

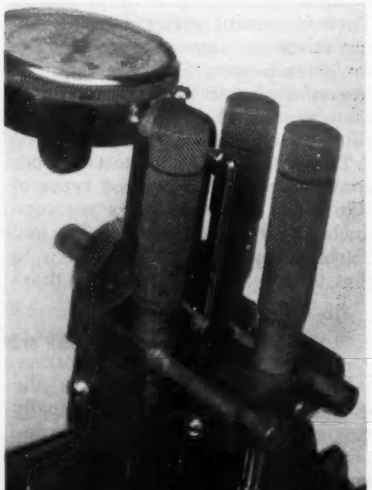

Figure 4. Tooth thickness measuring instrument.

PROFILE AND HELIX ANGLE CHECKS

Routine gear inspections include a series of profile checks taken along the tooth length, usually at the forward end, midpoint, and after end. The true involute reference line is conveniently set to read zero deviation at the pitch line. An original set of profile checks may show the results of the hardening and finishing processes, such as a "proud pitch line," or deliberate deviations like tip or root relief. Also, a single helix angle check normally is made by arbitrarily locating the correct helix angle reference line to read zero at one end of the tooth. This displays unintentional machining inaccuracies or designed variation of crown shaving or taper shaving.

After operation, the above readings are repeated. Their usefulness then lies in detecting shape changes, noting such things as tooth end loading, rounding out of the tips, root interference and other signs of non-uniform wear. Because the original lines of true involute and correct helix angle cannot be re-established for subsequent measurement, no indication is given of the amount of wear between successive readings.

CONTOURS SHOWING TOOTH WEAR

Let us consider that the helix angle deviation curve together with the several profile deviation curves comprise a three-dimensional contour of the gear tooth before operation (lines "x," figure 5). The surface is an accurate delineation of the departure from a true involute helicoid. After operation, the above curves are taken again in exactly the same location (lines "y," figure 5) and compared with the corresponding curves before operation. Thus far, the absolute relation between these surfaces is not established. All that is necessary to determine the displacement, however, is to know the wear at any one point of the grids under consideration. This is supplied by the tooth thickness measuring instrument. The thickness is easily measured at the midpoint of the pitch line. Separating the surfaces by that amount will show the wear between profile and helix angle curves as illustrated by the shaded areas of the sketch, figure 5.

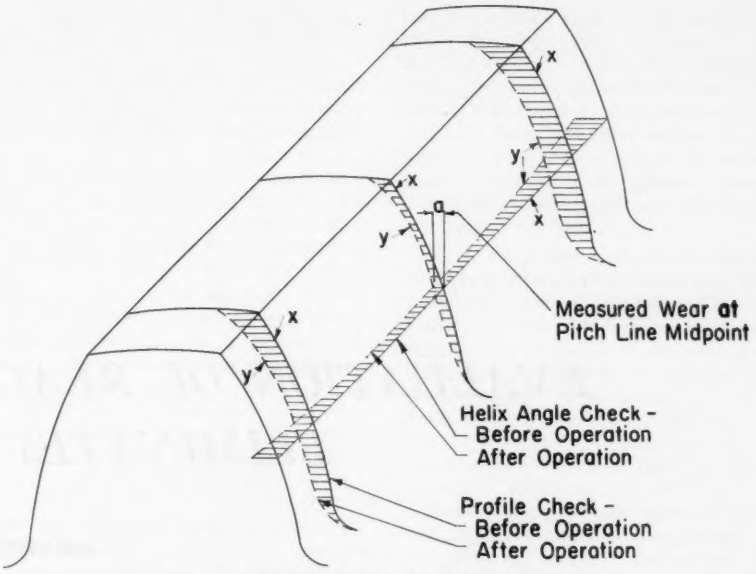

Figure 5. Tooth wear at pitch line and profile.

GRAPHICAL DETERMINATION OF TOOTH WEAR

The actual wear would be determined by two-dimensional plots such as those automatically produced by the gear measuring machines. With the wear known at one point, it can be deduced at any other through which a profile or helix angle check is made. A step by step procedure is outlined below.

a. Obtain wear at center of pitch line by difference of measured tooth thickness. Call this dimension "a."

b. Plot or trace helix angle curves obtained before and after operation on one set of coordinates, spacing the midpoints by the dimension "a." See figure 6.

c. Spacing of helix angle curves shows wear at any po'nt on pitch line. Measure dimensions "b" and "c" at points through which profile checks are made.

d. Plot or trace the profile checks on one set of coordinates, spacing the pitch line points by the dimensions "b," "a," "c," for fore, mid, and aft, respectively. See Figure 7.

e. Wear at any point on the profile is given by the spacing of the profile curves at that point. If a better picture of wear distribution is desired additional profile checks should be taken.

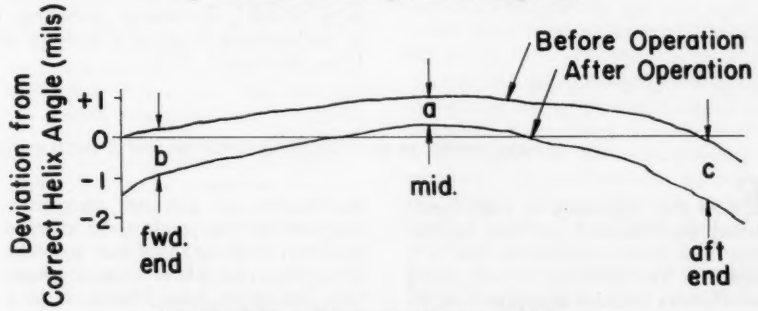

Figure 6. Helix angle checks plotted to show wear.

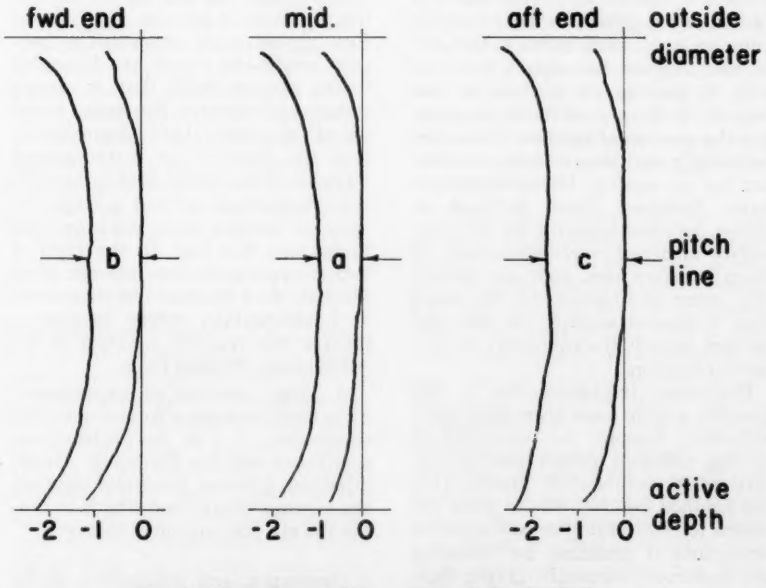

Figure 7. Profile checks plotted to show wear.

CONCLUSION

Application of the means and methods discussed herein should go far in advancing the reduction gear art.

J. S. MEURER

EVALUATION OF REACTION KINETICS ELIMINATES DIESEL KNOCK

ACKNOWLEDGEMENT

The author of this paper is J. S. Meurer, of Maschinenfabrik Augsburg Nurnberg (MAN), Nurnberg, Germany. The paper was presented at the Society of Automotive Engineers' Golden Anniversary Summer Meeting in Atlantic City, 12–17 June, 1955.

INTRODUCTION: IS MIXTURE FORMATION THE MAIN PROBLEM IN THE DIESEL ENGINE?

From the beginning of high-speed diesel development, mixture formation has been considered the key problem. The difficulty of achieving an effective mixture is appreciated by comparing the time available for that process in the diesel engine and in a carburetor engine. The diesel engine running at the same speed as the carburetor engine, has only 1/6 of the time to produce its mixture of fuel and air. It is very difficult to measure the process of mixture formation accurately and thus obtain a standard for its quality. Diesel engineers have, therefore, been inclined to blame deficient mixture for all difficulties in diesel combustion such as steep pressure rise, poor air utilization, noise and smoke. All the while they neglected another no less important aspect: the chemistry of diesel combustion.

Enormous improvements in the gasoline engine have been made possible only because we succeeded in getting sufficient insight into the nature of its combustion knock. This has enabled the chemists to work out means to counteract the performance limitations it produces by changing the molecular structure of the fuel. Diesel fuel, on the other hand, is the same today as it was at the time of Diesel and, apart from some standardization of physical properties such as ignition quality, no attempt has been made to adapt it in any way to the requirements of diesel combustion. However, heat liberation in a diesel engine and, consequently, its performance depend essentially on the combustion process; it is, therefore, almost more important to provide conditions which are favorable to the process itself, than to ensure a thorough mixture. For many years, diesel engineers held dogmatically that the ideal is an instantaneous mixture of the liquid fuel spray with the compressed air and a large variety of designs have been evolved to achieve this end. In the light of recent experience, this concept of an ideal air-fuel mixture can be refuted as fundamentally wrong because it ignores the reaction kinetics in the combustion of diesel fuels.

A large number of experiments have been necessary to arrive at this conclusion. One of the decisive experiments was the following: Direct injection systems generally rely on the combination of two effects to create the air-fuel mixture, namely

1. atomization and distribution of the fuel by the nozzle,
2. the motion of the air in the combustion chamber.

The various systems differ in the degree in which they make use of these two means. The atomization and dispersion qualities of a spray can be measured quantitatively with a more or less complicated test set-up.[1,2]* This becomes impossible when air motion is introduced.

In order to find out to what extent the performance characteristics of a diesel engine can be improved by better mixture formation, we selected an engine in which the mixture was essentially produced by the spray pattern without the help of any appreciable air movement. The combustion chamber was spherical as in previous MAN engines. We developed a nozzle for this engine which would distribute the fuel in conformity with the air distribution in the combustion chamber so that, at the end of injection, every fuel particle should find in its immediate vicinity the quantity of air required for complete combustion. In this manner, we attempted to reduce to a minimum the diffusion distances of the fuel vapors developed in the process. As this kind of distribution could be achieved before ignition occurred, it would not be disturbed by any turbulence arising in the chamber due

* Numbers in parenthesis refer to the list of references.

to localized ignition. Furthermore, the nozzle was designed to atomize the fuel as finely as possible.

High-speed photographs of the spray pattern and measurements of the fuel distribution in the spray by means of small collecting tubes provided numerical evidence that the nozzle produced the desired distribution. The development of the spray under atmospheric pressure indicates that the natural frequency of the needle valve was high enough to enable it to follow the fluctuations of the injection pressure without any appreciable delay and so to avoid periods of insufficient atomization. For small injection quantities the needle closes, under certain circumstances, repeatedly during a single injection period. At an air density equivalent to that in the engine, the velocity of the spray, as a result of the fine atomization and the absence of a spray core, was considerably lower; but the hollow cone quickly filled up with well atomized fuel. As desired, the spray was well adapted geometrically to the shape of the combustion chamber; furthermore, it could be proved that the fuel distribution in the spray matched the distribution of air in the combustion chamber. The results of the nozzle development, which, at least up to 1200 rpm, ensured a nearly ideal micro and macro mixture within the period of ignition lag, were most satisfactory. However, the tests in the engine turned out to be very disappointing. The characteristic diesel combustion knock was extremely loud, which was understandable, but contrary to all expectation the air utilization, in spite of the good fuel distribution, was very poor, resulting in heavy exhaust smoke over the entire load and speed range. This result confirmed the paradoxical conclusion that an "ideal" mixture formation is a handicap to combustion, i.e., that during the ignition lag, diesel fuel somehow cannot stand being mixed with air at all. Such a conclusion might have been inferred from other tests of a similar nature if numerical evidence had been available.

This conclusion made it necessary to look to reaction kinetics for the explanation of a phenomenon that obviously fetters mixture formation. Thus, attempting to produce a homogeneous mixture of the fuel with air before ignition occurs, as in a gasoline engine, had only aggravated some very undesirable features of diesel combustion.

A similar handicap exists also for other systems of mixture formation where an air motion is introduced in the combustion chamber to mix the air and fuel in a timed sequence so as to control heat liberation by progressive formation of the mixture during combustion. If, for improving mixture formation, either the air velocity or spray velocity or both were increased, the combustion noise became louder. If the fuel rate at the beginning of injection was reduced, the engine ran smoother, but there was an increase in exhaust smoke. In this maze of effects and counter-effects, diesel engineers have searched for the best way out. The best solution to be found was only a compromise between smooth running, fuel consumption and exhaust smoke which again became questionable with every change in operating conditions, like turning to a fuel of a different ignition quality. An intensification or acceleration of mixture formation resulted in most cases only in a deterioration in performance. It became obvious that the defects of diesel combustion did not stem solely from the limitations on mixture formation, but there had to be some specific reactions of the fuel which hampered combustion.

COMBUSTION SEEN IN THE LIGHT OF REACTION KINETICS

Although the phenomena of autoignition in the diesel engine and of combustion knock in the gasoline engine are closely related, there are still significant differences with respect to the sequence of events, the temperatures, and the state of the charge, causing considerable variations in the chain of reactions.

In neither type of engine do we find that direct oxidation of the original fuel molecule into its final products could cause self-ignition. Oxidation rather takes place through intermediate products whose reaction is extremely rapid. After 64 per cent of the charge has been burnt in an otto cycle engine, the temperature of the unburned gas is about 1250° F; that in a diesel engine is about 1100° F at the beginning of injection and rises very fast when reaction starts. Due to the heterogeneous mixture, the local temperatures are much higher than the average thermodynamic temperatures. The local flame temperatures reach a constant maximum value of 3800° F,[3] which is largely independent of the air-fuel ratio. This observation indicates, first, that the reaction in the diesel engine takes place with constituents that are still in the liquid or solid state which particles form radiation centers and, second, that the influence of local temperatures is still greater than would be obtained with homogeneous gas phase reaction.

Now we know that temperature exerts a predominant influence on the speed of chemical reactions. This is shown by the Arrhenius equation, which admittedly is exact only for a homogeneous gas phase reaction of perfect gases.[4] The mechanism underlying that equation is explained by the molecular motion dependent on temperature and the resulting collisions of molecules. If collisions of sufficient energy occur between fuel and oxygen molecules, then exothermic reaction starts; if no oxygen is available changes will occur in the fuel molecule, which become manifest as decomposition of the C-C and, especially, the C-H bonds.

True, the dependence of the latter process on the temperature cannot be measured since there is no measurable variable as in the endothermic reaction, but observations made in the engine suggest that a similar speed increase takes place as in the oxidizing reaction. In addition, it seems that such phenomena may also occur in the liquid phase, especially if evaporation is delayed, which, considering the finite velocity of molecular motions, is likely to happen in the high-speed engine.

In the gas phase and in the presence of oxygen, the path of the disintegration is via peroxide into radicals and, consequently, corresponds to the knock reaction in a gasoline engine.[5,6]

In the diesel engine, however, this process characterizes only the first step for which the necessary conditions regarding oxygen concentration and fuel evaporation are prepared during the ignition lag. The process cannot continue as it is impossible to feed enough oxygen for the rapidly increasing reactivity caused by the temperature rise. The activating heat added by the pre-reaction now causes decomposition of the C-H and C-C bonds in the molecule which clearly shows up in spectrographs where C-C bands are seen developing immediately after ignition has started.[5,6] In the degree that oxygen is supplied through mixture formation, reaction of the cracked products

takes place, but the rising temperature soon widens the discrepancy between cracking rate and oxygen supply so that eventually only pure carbon remains. Burning this carbon early enough presents a problem, as the diesel exhaust smoke shows, which is likely to be solved only with the aid of the catalytic influence of the water vapor produced during combustion, according to the equation $C+H_2O \rightarrow CO+H_2$, and subsequent reoxidation.

This catalytic influence can be fully effective only if the H_2O is formed close to the molecule, i.e., if the H_2 and C reactions in the molecular compound commence at least simultaneously—the H_2 reaction always proceeds at a faster rate—and before disintegration to pure carbon has taken place. The only way to achieve this without starting the temperature propelled avalanche of thermal disintegration, is by means of pre-oxidation that proceeds sufficiently slowly to enable the reactive surface of the molecule to be suitably transformed.

These phenomena are well exemplified in the gasoline engine where diffusion has time enough to produce an almost molecular mixture so that the exhaust is practically free from smoke. But even here one can produce smoke without changing the air-fuel ratio or mixture formation which proves that, at high temperatures, the H_2O diffusion rate cannot keep pace, even over minimum distances, with the rate of disintegration. Thus, if the compression ratio of a gasoline engine burning paraffin-base fuels is increased so that knocking involves an ever greater fraction of the charge, smoke will appear in the exhaust. In that case, the temperature and the disintegration rate of unburnt charge reach the point where the catalytic effect of the H_2O begins to lag behind and fails to have any effect on the molecular changes.

Regarding the influence of temperature on the physical mixing process, we find that there is very little acceleration due to temperature.[9,13] The mechanical distribution by the nozzle and the air motion is influenced by the temperature only as far as it affects the air density; in the engine, however, temperature variations go together with variations in pressure so that no conditions accelerating the distribution can arise. With evaporation this is different.

In short, we find ourselves confronted with the fact that the higher the temperature in the diesel engine the less chance we have to produce a perfect mixture of the air with the vapor formed from the liquid particle. The fuel molecule disintegrates as described above, while the oxygen, being supplied at a relatively slow rate compared with the molecular disintegration, is used up in a chain of autoignitions of activated fractions before a homogeneous mixture can form, leaving a carbon skeleton which it is very difficult to oxidize in the time available. Certainly, the enormous acceleration which temperature imparts to all chemical processes, ensures self-ignition at the right time, but what helped to bring about ignition is very undesirable in the subsequent phases of reaction. From the view point of reaction kinetics, the irresistible avalanche of disintegration deteriorates the fuel, i.e., it places the most sluggish reaction at the end of combustion. This could be avoided if means were to be found to adapt the physical mixing process to the high rate of chemical reactions, even though nothing much would be gained thereby because of the resulting steep pressure rise which, being a source of noise, is a thing we want to avoid. However, one might try to achieve it by delaying the initial reaction by cutting down the oxygen supply, which would produce some improvement in this particular respect but at the cost of more exhaust smoke. This is because, at the high local temperatures, the avalanche set off by self-ignition continues irresistibly until the fuel has broken down to pure carbon. This vicious circle explains the limitations of mixture formation mentioned earlier. Autoignition in itself is fine, but its consequences are less desirable, and logically it should be limited to the smallest possible portion of the fuel.

On the other hand, this process of disintegration of molecules is not the only one possible for the combustion of gas oils. If gas oil is mixed with air prior to combustion—at low temperatures it should be emphasized—as is done in a blow torch, the spectrum of the flame will show bands in the ultra violet range indicating that oxidation proceeds via the radicals CH, C_2 and OH, and only later a continuous spectrum develops in the visible range of carbon monoxide.

In the engine, combustion starts with the continuous spectrum indicating broken up carbon compounds. While the blow torch operates without smoke, the combustion in the engine tends to form soot, i.e., the path of reaction is fundamentally different and it is obviously essential for complete combustion that fuel and oxygen should be heated up together or at least that provision be made for starting the oxidation gradually.

Attention should be paid to another observation. In 1908 Rieppel [11] advanced a theory stating that the supply of a little heat causes diesel fuels to form oil vapors, and it is these that burn in the engine. Wollers and Ehmcke [12] found with the ignition-point tester that these oil vapors have a much higher ignition point than the liquid fuel from which they are formed and that the temperatures reached at the end of the compression stroke are too low to cause their ignition.

Evidently, the ignition point is influenced by the mechanism of mixture formation, being low for vapors formed by heating fuel droplets with hot air, and high for vapors that are formed by heating the fuel in the absence of any appreciable amount of air or oxygen, and subsequent diffusion in air. This observation is confirmed in the M-engine where it has been put to good use.

APPLICATION OF REACTION KINETICS TO THE ENGINE

There are two phenomena in diesel combustion that cause most trouble and which we desire to eliminate:

1. Combustion noise, a more or less intense knocking depending on the fuel properties.
2. Exhaust smoke which develops before the excess air is fully used up.

From reaction kinetic concepts we can derive a few rules that we have to observe in order to be able to eliminate these drawbacks:

1. Limit to a minimum the portion of the fuel involved in autoignition.
2. Allow the fuel to oxidize gradually and try to heat fuel and air together.
3. Mix the fuel with the hot air fast enough to effect a stoichiometric air-fuel ratio before ignition starts and make sure that no more fuel is mixed at any time than can burn with a permissible pressure rise.

These requirements cannot be met with the conventional methods of mixture formation in diesel engines. Certainly, it might be quite possible to follow rule 1 by employing a fine pilot jet for ignition although nozzle orifices of such a small diameter are undesirable in practice; the real diffi-

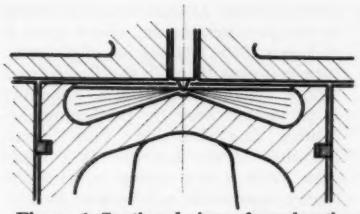

Figure 1. Sectional view of combustion chamber of standard direct injection diesel engine.

culty is in complying with rules 2 and 3 at the same time. Because rule 2 calls for caution in bringing the fuel into contact with the hot air, while rule 3 postulates: mix the fuel with the air in successive minute portions, the rate of mixture of each portion being many times faster than that of the preceding one. Furthermore, for those portions of the fuel entering the chamber later in the succession, it seems impossible to observe rule 1, as it makes it necessary to change the properties of the same fuel from highest ignition quality to maximum anti-knock rating. But to operate an engine on two fuels, which might be a solution, has never been desirable.

If we consider a diesel engine with direct injection and air motion of conventional design (Fig. 1) from the point of view of the above rules, we find that rule 1 cannot be complied with, since, even during a very short ignition lag, approximately one half of the fuel is already finely sprayed into the hot air and the quantity involved in initial self-ignition can no longer be controlled. This also prevents the fulfillment of rule 2.

In the combustion chambers of such engines, a rotary air swirl is frequently employed which tears off the atomized fuel from the fuel jets entering at right angle. Even if the spray is very coarse, this ensures that a maximum surface of the fuel is exposed to the hot air. During precisely this period when rule 2 calls for a slow pre-oxidation, the relative movement of air and fuel is at a maximum, as the fuel particles are being deflected from their original path by the force of the air. The air swirl is not really desirable at that moment and, in order to comply with rule 3, it should reach its maximum intensity only, in the next phase. Actually at that time the relative movement of air and fuel decreases because the fuel particles have in the meantime been turned into the direction of the air stream.

We do not mean to say that such "air distributing" engines are not practical. The fact is, they perform very well, but they suffer from the drawbacks mentioned previously, which become especially noticeable when fuels of varying ignition qualities are used.

The provision of rule 1 could be fulfilled, we found, only by providing an external source of ignition for the remainder of the charge, or rather an ignition that can at least be timed. A precondition is that an air-fuel mixture be formed which does permit ignition by external means before autoignition occurs, i.e., the ignition point of the mixture must be as high as possible. As mentioned earlier, such mixtures are obtained by means of careful heating combined with gradual oxidation as prescribed by rule 2. It is clear that neither can be achieved with a droplet moving in hot air with tremendously high heat transfer rates.[13]

According to rule 2 the fuel must not be allowed to get into contact with the air in the first stage and therefore it must not be atomized. But as it is to be burnt in the combustion chamber eventually, it must be kept there in a non-atomized form and at a temperature where gradual pre-oxidation and progressive mixture according to rule 3 is possible.

The most suitable spot for this is the surface of the combustion chamber, the temperature of which is sufficiently below the gas temperature to protect the fuel from rapid heating. Thus, at the beginning of mixture formation a process has been adopted whose retarding effect on reaction is well known and dreaded: Fuel impingement on the wall. But the only reason this is bad is because reaction has already begun while the fuel was penetrating the hot air. Troubles experienced in conjunction with this latter condition have given the idea of wall contact bad repute although it was actually applied in engines some 40 years ago.

The need for simultaneous cooling and evaporation implied by the second rule could best be met by spreading a thin fuel film over a maximum area of the combustion chamber. It had to be thin in order to make cooling sufficiently effective right through the fuel film to prevent the top surface in contact with the hot gases from being heated too fast, as a result of the temperature gradient through a thick layer.

Slow and uniform pre-oxidation also necessitates a certain surface area. There is certainly more turbulence in a fuel splash shooting along the wall of the combustion chamber than in a fuel droplet; thus, the fuel particles are partly exposed to the oxidizing effect and partly to the cooling effect of the wall. As a result, the combustion chamber wall acts as an intermittent carburetor performing a very complex function. The fuel being already in a highly active state is still under the control of the wall which, therefore, through its specific properties is well capable to exert a catalytic effect on the course of the reaction.

Finally, rule 3 has to be complied with. So far the indispensable mixture with the air has not yet taken place and, as we know, it should proceed at an extremely high rate. Without this rapid mixing process, the results of depositing the fuel on the wall to such an extent would be entirely negative with respect to air utilization and fuel consumption. For the diffusion rate of the fuel vapor which develops on the wall is much too low to ensure mixing at the necessary high rate. As the only suitable means there remains an air motion which, in view of the application of the fuel in form of a film, should be well-directed and maintained throughout combustion undisturbed by the latter. It is certainly easier to provide a turbulent air motion by squish, but such a swirl is limited to a short period and breaks down due to expansion of the charge following ignition.

In order to peel off the fuel film in layers, a rotary air motion around the cylinder axis is most suited. It should be produced during the suction stroke and be maintained by the inertia of the air long enough to be still noticeable during the exhaust stroke. The rotary velocity of the air in the decisive phase of mixture formation can be efficiently increased and a favorable distribution of the air in the combustion chamber can be obtained, if the diameter of the latter is kept smaller than that of the cylinder and if care is taken to ensure that a maximum portion of the air gets into the combustion chamber.

However, before we apply such a violent air motion, we must investigate whether we can reconcile it with the requirement of rule 2 for slow oxidation and minimum air contact. Breaking up of the fuel jet occurs as a result of the friction between the jet surface and the air, which is at a minimum when the jet and the air have the same velocity. The nearest approach to this state is made by directing the jet tangentially to the air motion on to the wall. If the jet

hits the wall at a distance from the nozzle where it only just starts breaking up, excessive atomization will be prevented, no matter whether it is injected tangentially, against, or in the direction of rotation. If the fuel jet and air move in the same direction, the air will assist in spreading the fuel film.

Selecting the proper distance of the nozzle tip from the wall of the combustion chamber will at the same time help to comply with rule 1. It has been found by means of high-speed photographs of fuel injection into a hot bomb,[13] that the first ignition was always initiated by a small cloud which formed near the nozzle. Obviously, this small fuel cloud develops at the very beginning of injection and, due to the initial impact on the air, consists of very fine particles, the aerodynamic resistance of which is higher than their inertia. These particles, therefore, lag behind the jet. The nozzle tip is located at a point where it is not directly exposed to the rotary air motion, providing a distance between the tip and the wall which enables these fine particles to separate before the fuel jet hits the wall. Thereby it is possible to subject these particles to the normal autoignition of fuel distributed in air. In this manner, the small portion of the fuel which alone, according to rule 1, should self-ignite, is obtained without an additional nozzle orifice. To achieve self-ignition of this portion, advantage is taken of the low ignition point of fine fuel fog formed in the presence of oxygen. The details of these processes were brought to light by experiments and, as will be shown later, very convincing evidence was found that they really do take place in that manner.

According to rule 3 it is the function of the air motion to produce the mixture so rapidly that at least a stoichiometrical air-fuel ratio is attained before ignition sets in. But in addition, rule 1 requires that autoignitions be avoided. The measures so far proposed create favorable conditions to meet both requirements.

1. The fuel which at the beginning shoots across the combustion chamber wall at nearly the speed of the air is considerably retarded in the process and, as the mixture formation period approaches its end, the velocity difference between the rotating air and the fuel increases progressively. In effect, this is the opposite of what happens in engines where the fuel is injected at right angles to the air swirl. There, the relative velocity of air to fuel decreases as the droplet is reduced by evaporation in the course of mixture formation, so that its eventual velocity conforms with the direction of the air motion and that it moves along enveloped in its own vapor cloud. Apart from that, each liquid droplet constitutes an undesirable accumulation of fuel which under engine compression densities necessitates for correct mixture approximately 6.5 times the air volume required by fuel vapor of equal volume. Once deposited on the wall, the fuel hardly leaves it in the liquid state and, therefore, the risk of wide differences of fuel concentration in the mixture is eliminated.
2. Evaporation of the fuel on the combustion chamber wall is not instantaneous but is controlled by the wall temperature and by the temperature difference between the wall and the gas. The total kinetic energy stored in the air rotation affects only a fractional amount of the vapor at a time and thus can achieve the prescribed rapid mixture followed immediately by combustion. Thus, the same process that in the conventional methods of mixture formation takes place only once, involving the complete fuel charge, is here successively repeated many times.
3. In selecting the wall temperature, care must be taken that it is high enough to initiate evaporation, but not so high as to cause thermal decomposition of the fuel molecules to the point of formation of solid soot. Since, due to heat dissipation, the air temperature is lower, initially, near the wall than in the center of the combustion chamber, the desired slow oxidation takes place partly as a surface reaction in the boundary layer between the liquid and vapor phase and partly in the vapor phase. The evaporating fuel particles quite obviously consist of decomposition products of the first stage (aldehydes, ketones, olefins) that are formed under moderate heat and an extreme air deficiency; these ignite spontaneously at a higher temperature than does vapor formed in the presence of hot air. Consequently, the induction time for these mixtures at the temperatures attained through compression in the diesel engine is now long enough to prevent autoignition within the period during which they are mixed with hot air. Therefore, external ignition and subsequent combustion are possible before the portion of the mixture involved can ignite spontaneously. The instant of ignition is evidently determined by the ignition limit set by the fuel concentration being passed, and the means of ignition are the incandescent fuel particles generated in the limited autoignition according to rule 1. This process is repeated in rapid succession in different places, and at any one time involves only that small mixture fraction which, depending on the rate of evaporation, passes the ignition limit at that time. Similarly to the gasoline engine, where there is no knock if the last portion of the mixture can pass through the flame front before self-ignition occurs, knocking is prevented here by producing, igniting, and burning very small amounts of the mixture at a rapid rate. Thus it is possible to trick the high compression ratio out of its traditional function of triggering self-ignition. This method is also adaptable to the gasoline engine.

What has been described in the foregoing is well confirmed by the engine in operation, although the practical design suffers from a few compromises, especially regarding the removal of the fuel from the wall, which is effected at such a high rate that the increasing gas temperature tends to assist the decomposing reaction.

There is also an interesting thermodynamic advantage in evaporating the fuel on the wall. If the liquid fuel is distributed in the hot air in the combustion chamber, the evaporation heat can only be taken from the heat of the air produced by the compression work. This constitutes a loss which is shown schematically in the temperature entropy diagram (Fig. 2). If the fuel is evaporated

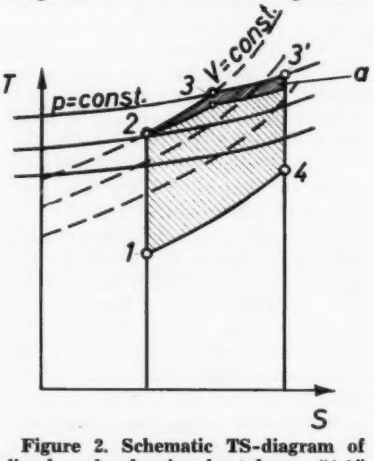

Figure 2. Schematic TS-diagram of diesel cycle showing heat losses "(a)" due to evaporation of fuel.

on the wall, the heat of evaporation is drawn from the piston and not from the working medium. The heat in the piston, however, being essentially waste heat, can thus be partly recovered in order to avoid a loss of available energy in the working medium. Admittedly, this is a very small amount, approximately 1.8 per cent of the heating value, but nevertheless it is of some importance where it is desirable to obtain a somewhat longer combustion with the same fuel consumption.

COMBUSTION CHAMBER DESIGN FOR THE M-SYSTEM

There are several ways of translating into practice the rules and instructions given in the foregoing.

The piston is designed with a combustion chamber in the center forming a little more than half a sphere. The throat of the chamber has a recess through which the fuel jets reach the wall of the combustion chamber at an acute angle. The nozzle has two orifices of .015" diameter each and its operating pressure is 2500 psi. During the suction stroke, a rotary motion of the air is induced in the cylinder in the same direction as the fuel jets. The rpm of the air swirl is considerably increased when its diameter is reduced at top dead center from that of the cylinder to that of the combustion chamber. The fuel is applied to the wall of the combustion chamber in two splashes which spread rapidly and eventually flow together and form a continuous film which, as can be seen from the surface appearance of used pistons, covers half the combustion chamber surface. Assuming uniform distribution of the film, its thickness can be calculated from the quantity of fuel injected and is .6 thousandth of an inch at full load.

The wall temperature of the combustion chamber is maintained at about 640° F for full load by an oil cooling arrangement (Fig. 3). A nozzle in the crankcase throws up to 2 quarts of oil per minute against that side of the combustion chamber where the fuel film is deposited. Cooling of the piston might be effected without oil by suitably dimensioning the cross sections of the material, but oil cooling makes the piston lighter and also has the advantage that the pistons remain very clean. When the cold engine is started, oil is instantly available at the piston rings and the oil supply of the engine warms up quickly. It is somewhat difficult to control the oil consumption; a very satisfactory solution was found, however, in the present case in the form of wide return channels in the piston skirt.

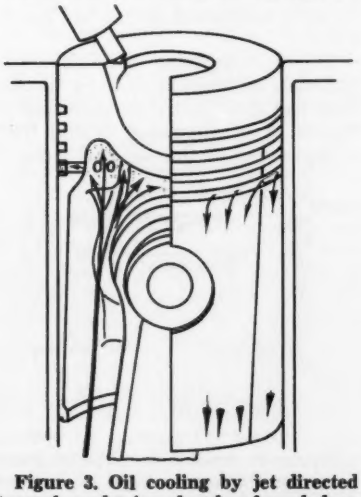

Figure 3. Oil cooling by jet directed toward combusion chamber from below.

Normal Diesel System		MAN M-System	
100% of injected fuel		100% of injected fuel	
1) Injection into air		1) Injection of liquid fuel	
		about 5% in the air	about 95% on the wall
2) Mixing with hot air.	of liquid fuel	same as in normal Diesel engine (see left)	2) Evaporation at low temperature under lack of oxygen Slow preoxydation.
3) Evaporation at high temperature in presence of oxygen.			3) Mixing of fuel vapor with air.
4) Autoignition of incontrollable quantities of fuel (low ignition temperature); decomposition to carbon.			4) Ignited by incandescent carbon particles produced by autoignition of air distributed droplets
5) Combustion with high reaction rate at the start, increasingly inert toward the end.			5) Combustion before autoignition occurs

Figure 4. Comparison of mixing and combustion process in a standard diesel and an M-system diesel engine.

All pre-requisites for the successful adoption of the described system are now fulfilled:

1. Deposition of the fuel on the wall in the form of a film with a small amount of fuel being separated for distribution in the air and initial autoignition.
2. Direction of the jets tangentially to the direction of the air so that the undesirable mixture of the liquid fuel with the hot air is reduced to a minimum.
3. Vaporization in the presence of very little air at low temperature and gradual pre-oxidation as well as rapid mixture of the fuel vaporizing per unit time and a properly timed external ignition.

Although the individual phases overlap, it is possible without oversimplification to make a comparison between a conventional direct-injection engine and the M-system (Fig. 4). It can be seen clearly that for the greater part of the fuel the M-system interchanges points 2 and 3 of the standard diesel system.

TEST RESULTS

The engine test results of the new system are amazing. In particular, the typical diesel knock has disappeared over the entire speed range, even during idling and starting of the cold engine and this has been obtained without sacrifice in specific output or in fuel consumption. Moreover, these characteristics are, within wide limits, independent of the fuel characteristics including the cetane number.

As can be seen from Fig 5, which shows the cross-section of an engine of 4.4" bore and 5.5" stroke, the M-system has not in any way complicated the design. It is essential to locate the valves in the central plane of the cylinder where they can be designed with a maximum cross-section. This is of special importance for the intake valve because the measures necessary to produce the air rotation reduce the effective port area.

The specific fuel consumption of a 6-cylinder engine with the above dimensions is shown in the diagram, Fig. 6. The curves of equal consumption extend over wide speed and mep ranges. There is no appreciable narrowing of the spacing in the region of high or low speeds, indicating that

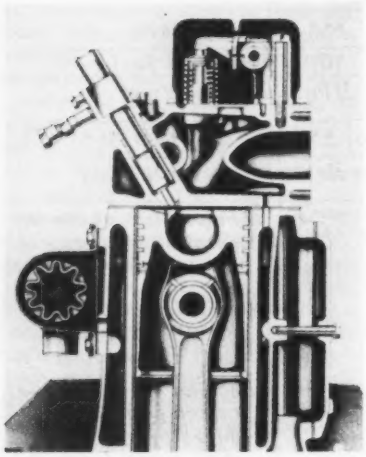

Figure 5. Sectional view of production engine, 4.4 in. bore, 5.5 in. stroke, 6 cylinders in line, max. output (supercharged) 200 hp at 2300 rpm.

there is no definite point beyond which mixture formation is a limiting factor. A notable fact is how far the curves extend into the region of low speeds. In road service, these engines show a surprising flexibility and even at 300 rpm combustion is still uniform enough to permit the full-load fuel quantity to be injected without trouble. Below 800 rpm, the injection pump, controlled by the governor, supplies an extra starting charge which improves flexibility still more (Fig. 6, full-load curve).

The turbo-charged version of the same engine has a peak output of 200 hp and over wide speed and mep ranges its consumption is less than 0.37 lb/hp hr (Fig. 7).

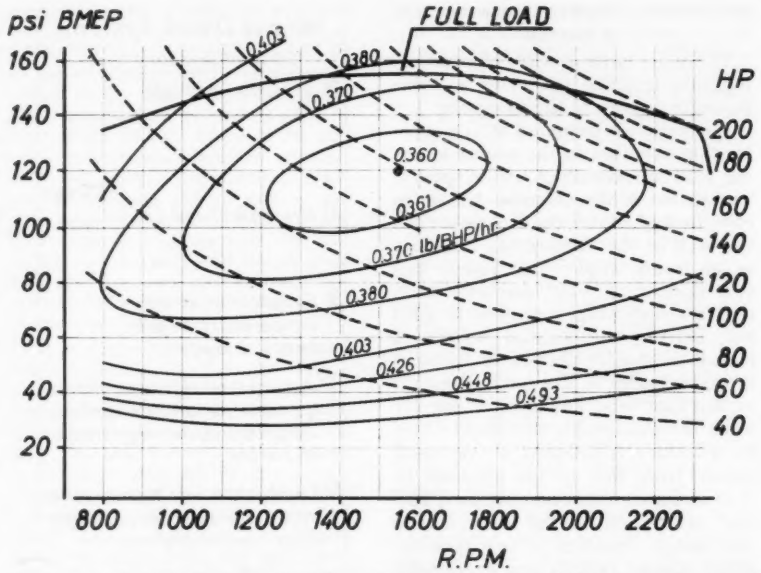

Figure 7. Specific fuel consumption characteristics in relation to engine speed and mean effective pressure, showing also full power curve, for 6 cylinder engine, D 1246 M, with exhaust turbo-supercharger.

COMPARISON OF SOOT FORMATION

Interesting conclusions with respect to the reactions during mixture formation can be drawn from the amount of soot in the exhaust and the analysis of the used oil. If the discoloration of the diesel exhaust smoke is measured, it will be found that there is a marked reduction when the mean effective pressure decreases, which is readily explained as the result of increasing excess air. However, the influence of the air-fuel ratio must be eliminated if, in order to clarify the mechanism of combustion, we want to find out what percentage of the carbon supplied in the fuel is obtained in solid form in the exhaust. This is done by relating the amount of soot not to the exhaust gas quantity but to the quantity of fuel injected, in other words by making the amount of filtered exhaust proportional to the fuel quantity.

The investigation covered three different methods of mixture formation and the results are recorded in Fig. 8. It is surprising to find that, independent of the air fuel ratio, a

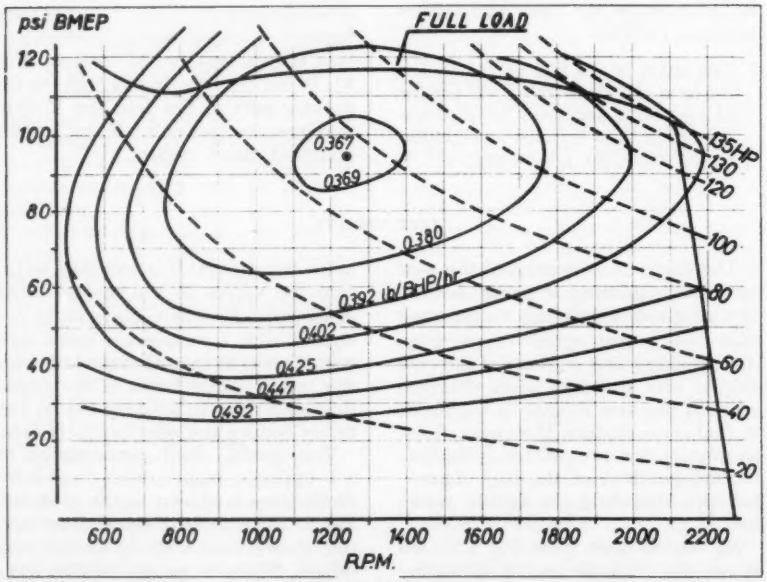

Figure 6. Specific fuel consumption characteristics in relation to engine speed and mean effective pressure, showing also full power curve, for 6 cylinder engine, D 1246 M, with natural aspiration.

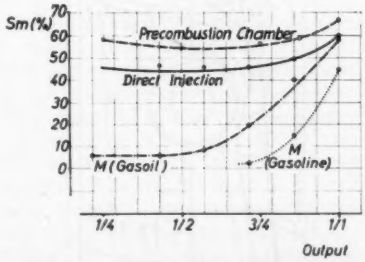

Figure 8. Smoke in exhaust gases measured for same weight of injected fuel, for several load conditions, at 1400 rpm.

precombustion chamber engine and a direct-injection engine transform nearly the same percentages of the fuel into free carbon. This clearly indicates that soot formation in the diesel engine is essentially due to reaction kinetic causes. Only in the power range above 75 bmep does the influence of mixture formation become noticeable. The soot formation in the M-system shows a different trend. In the range up to 50 bmep soot formation is within the limits of a gasoline engine and then approaches the characteristic of the diesel engine because the realization of the M-system in the present design still suffers from some compromises in the region of high mean effective pressures.

This result agrees very well with the analysis of used oils in engines employing the M-system (Fig. 9). Column 1 gives the data of the direct-injection and M-system versions of the same engine under equivalent operating conditions. It can be seen that the percentage of constituents which are insoluble in standard benzene is much lower in the M-system engine while, and this is of particular interest, the acidity of the oil in that engine is a fraction of that arising in the direct-injection engine. The latter result clearly suggests the different direction of reactions which no longer form acetic acid and formic acid but take place via ketones, olefins and aldehydes. From the analysis one may calculate the "sludge rate," a value which indicates the amount of benzene insolubles produced in an engine per hp and mile.

Whereas the value found for orthodox diesel engines is 4.6 oz per 1000 miles and 100 hp, for M-engines it is as low as 1.1 oz per 1000 miles and 100 hp. In gasoline engines it is approximately 1.1 oz per 1000 miles and 100 hp. In other words, the M-engine equals the gasoline engine in low oil contamination.

Full Load - Endurance Test Run.		
Engine Type	8 × 4.53" × 5.51" 180 HP Direct Injection	8 × 4.53" × 5.51" 210 HP M - System
Hours of Test Run	60	60
Equivalent Miles	2620	2620
Neutralization Number	0.3 %	0.0 %
Insolubles in Benzene	0.8 %	0.28 %
Specific Sludge Formation	2.3 oz./1000 Miles – 100 HP	1.1 oz./1000 Miles – 100 HP
Road Test (City Bus Service)		
Engine Type	6 × 4.41" × 5.51" 130 HP Direct Injection	6 × 4.41" × 5.51" 130 HP M-System
Stat Mile	2240	2240
Neutralization Number	0.83 %	0.53 %
Insolubles in Benzene	1.9 %	1 %
Specific Sludge Formation	6.0 oz./1000 Miles – 100 HP	3.1 oz./1000 Miles – 100 HP

Figure 9. Chemical analysis of lube oil of standard direct injection engine, and of M-System engine, after same service time.

INFLUENCE OF THE JET DIRECTION IN THE COMBUSTION CHAMBER

If the concept of wall contact influencing smoke formation is correct, then it should be possible to vary the latter by modifying the direction of the jet in the combustion chamber which in conjunction with the air motion controls the degree of wall contact and the area of the film. That this is so could be easily proved by rotating the nozzle in the combustion chamber. A three-hole nozzle was used with only one orifice open and, therefore, the amount of fuel injected was reduced to one third. In Fig. 10, the alternative jet directions are given together with the measured exhaust discoloration. According to the orthodox belief that rapid distribution of the fuel in the air is essential, jet I ought to have given better combustion than jets II and III and especially better than IV, which latter directly hits the wall. However, it was precisely jet IV, which, as well as III, caused practically no discoloration of the exhaust, while the "good" jet I produced about 4 times more smoke at 1900 rpm. The differences in fuel consumption were small but jet I produced a distinct noise which nearly entirely disappeared with jet III.

It has been pointed out frequently in the relevant literature that for favorable combustion the injection should be directed into the zone of air turbulence. This zone is no doubt in the plane of the combustion chamber throat, but, as can be seen

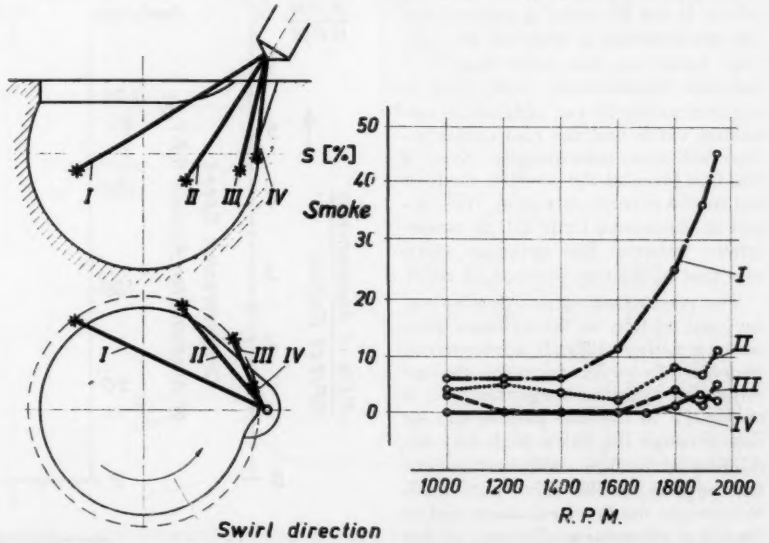

Figure 10. Influence of direction of fuel spray upon exhaust smoke (Injection well below plane of chamber throat.)

from Fig. 11, jet A fails at high speeds to give the smokeless exhaust obtained by jets III and IV of the preceding illustration. The reason is that the squish pushes the jet off the wall and also tears too much fuel out of it.

It should be added that there is an interaction between the circumferential velocity of the air in the combustion chamber and the jet direction, inasmuch as a higher air velocity enables more fuel to be brought into contact with the wall. However, the heavier air drag then makes it necessary to place the jet more in the direction III, because otherwise the amount separated for initiating self-ignition would become too small.

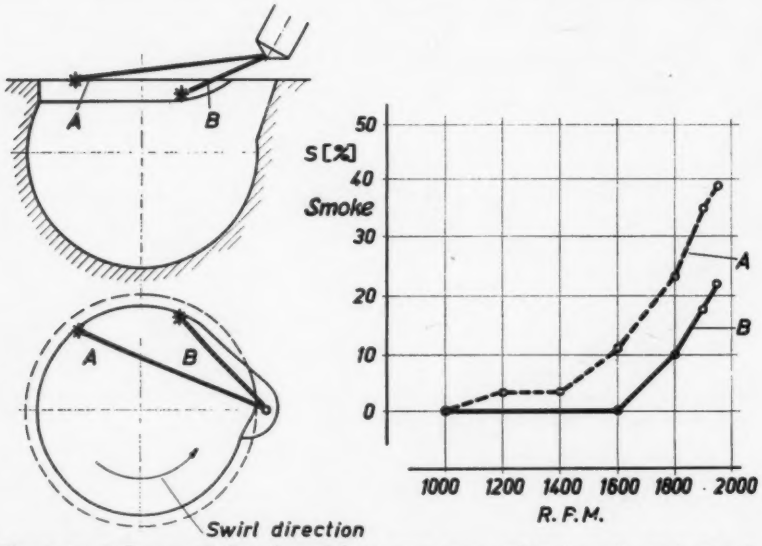

Figure 11. Influence of direction of fuel spray upon exhaust smoke (Injection in plane of chamber throat.)

INFLUENCE OF AIR MOTION

It will be appreciated that the influence of the air swirl in the M-system is very great and that the atomizing effect of the nozzle is secondary in importance to its directing effect. If the air swirl is omitted and the jet direction is retained, the output, based on the same degree of exhaust discoloration, will drop to approximately 57 per cent of the optimum value and the fuel consumption will rise substantially. Even if the full force of the swirl is made to act in the reverse direction, the output at the smoke limit will be somewhere between the optimum value and that of the test without air swirl.

The production of an effective rotary air motion in the cylinder presents a rather difficult aerodynamic problem. In order to make the air enter the cylinder tangentially, it is necessary to throttle part of the air flow through the valve port. Any reduction of the flow coefficient in certain sections of the valve port tends to increase the flow resistance and to limit the volumetric efficiency of the engine; at the same time it increases the pumping losses of the gas change cycle. To compensate for the increased flow resistance by means of a larger intake valve is very seldom practicable.

The loss in a well-designed intake is relatively low at moderate rotary velocities of the air. The results of static flow tests in intake ducts are reproduced in Fig. 12. The suction pressure in the cylinder was measured which, with a given valve lift, is required to draw in the air at an axial velocity corresponding to a mean piston velocity of 2000 ft/min. An anemometer was used to determine the circumferential velocity of the air swirl on a circle of 0.7 d_{cyl} (cylinder diameter). Another scale is shown in Fig. 12 indicating the ratio between anemometer speed and engine speed at a stroke of 5¾".

Curve (a) is plotted for a duct fitted with a masked valve, the mask angle being increased in steps as indicated on the figure. The circumferential velocity increased proportionally and a higher suction pressure had to be produced in the cylinder. The mask angles employed in the M-system engine vary between 110° and 120° and it is seen that the anemometer speed then corresponds to about 8 times the engine speed. The inlet pressure drop increased to approximately 1.5 times that for the non-masked valve.

Curve (b) is drawn for a similar test made with a non-masked valve where the swirl was imparted by the special shape of the duct. It can be readily seen that this design produced the required rotary velocity of the air with less flow resistance, and the inlet pressure drop increased only to 1.3 times that for the non-masked valve. It is, therefore, possible to

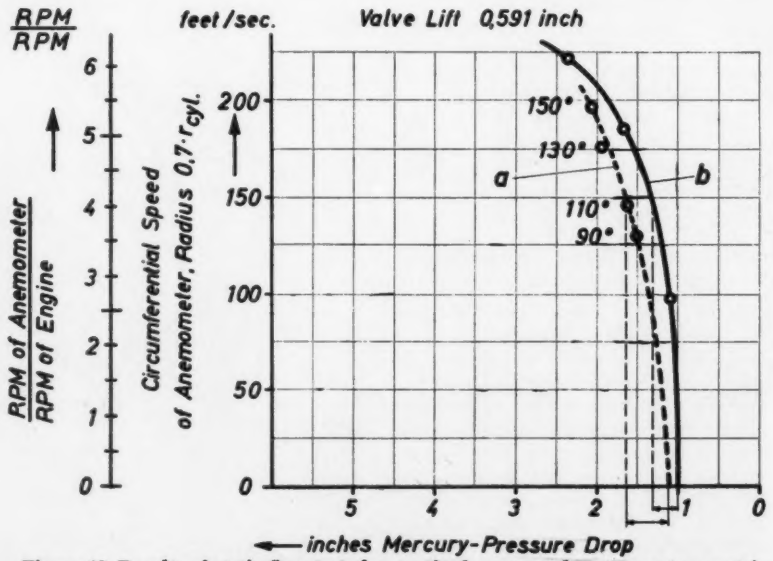

Figure 12. Results of static flow tests for required pressure drop to create a certain swirl.

keep the losses due to the means for inducing the air swirl at a minimum.

A considerable increase of the swirl speed is obtained by making the diameter of the combustion chamber smaller than that of the cylinder. Allowing for friction losses, it is safe to assume that the swirl speed in the *combustion chamber* will be at least 6 times the engine speed.

COLD-STARTING ABILITY

It is essential for every automotive engine to be able to start quickly even at very low ambient temperatures. It is unlikely that the fuel which in the M-system is deposited on the cold wall of the combustion chamber, will vaporize in time. Only the air-distributed fuel fraction separated from the jet for initial autoiginition may do so; but being very small, the pressure rise attained by its combustion is insufficient to overcome the friction resistance of the engine and so to start the engine on its own.

To remedy this deficiency, two measures have been introduced:

1. The injection of the fuel pump was increased to 180 per cent of the full-load quantity in the range of starting speeds. Consequently, the air-distributed fuel fraction became large enough to ensure sufficient heat liberation after ignition to start wall vaporization. The starting time nevertheless remained longer than that of conventional engines fitted with glow plugs and the exhaust showed unburnt fuel vapor during the first 30 seconds.
2. Perfectly reliable and quick cold starting was ensured by means of a small compressed air burner which is illustrated in Fig. 13. Compressed air is supplied (a) from the air receiver of the brake system or by means of a hand pump through a pressure regulating valve (b) to an air nozzle (d) blowing over a fuel nozzle. Some fuel is drawn from the nozzle and, after mixing with the air stream, is ignited by means of a spark plug (e). The small flame developing reaches approximately into the middle of the intake pipe where it is met by an air stream emanating from nozzle (f) which, being heated by the gases, is discharged through the filter element of the air cleaner into the open. The filter is heated and when, after about 20 to 30 seconds, the starter is operated, the engine draws the cold air through the highly preheated filter. Without any of the oxygen of the intake air being consumed, the latter is preheated by about 110° F, which is sufficient to enable the engine to start instantaneously. This cold starting unit may be operated as long as the engine is warming up because the flame is nearly self-sufficient due to the compressed air supply, and consumes scarcely any oxygen from the intake air. In case the air pressure in the brake receiver is zero, there is a non-return valve which ensures that, during the first revolutions of the engine, the brake compressor pumps the air to the burner before any air is delivered into the brake system. The unit, which operates on gas oil, is controlled by a push-button fitted on the dash board. Using gas oil for fuel and allowing for a preheating time of 30 seconds and a starter speed of 110 rpm, the engine will run on its own within 9 seconds at 4° F below zero. This arrangement provides most satisfactory cold starting under normal service conditions.

If fuels of a very low cetane number, such as high octane gasolines, are used, another measure must be taken in addition to the cold-starting device. It is not at all difficult with the above mentioned equipment to ensure ignition and starting of the engine, but a longer preheating time is required when fuels of low ignition quality are used in order to attain maximum speed and full power. But this difficulty, too, was successfully overcome. The cold-starting ability of a diesel engine is roughly proportional to the amount of fuel which is "air distributed," i.e., which is able to undergo autoignition or at least to participate in the preparatory stages. The more the wall application of the fuel can be changed into air distribution, the better will be the cold-starting ability. A first attempt was made by providing an additional third fuel jet directed into the center of the combustion chamber so as to bring about "air distribution." The effect on the cold-starting ability of the engine was quite marked. However, under full load service, that advantage was offset by increased exhaust smoke and rough running of the engine.

Rotating the entire nozzle for low-temperature starts is also very effective but it is simpler to vary the velocity or direction of the air swirl in the combustion chamber. If the air swirl is reversed by turning the masked intake valve through an angle of 180°, the jet, being directed against the air stream, will be broken up considerably. Even a reduction of swirl velocity alone improves the cold-starting ability appreciably. A combination of all three measures is most effective and, at a temperature of -4° F, enables the engine to be run up to operating temperature and peak speed within a very short time even when leaded gasolines of 80/86 octane are used.

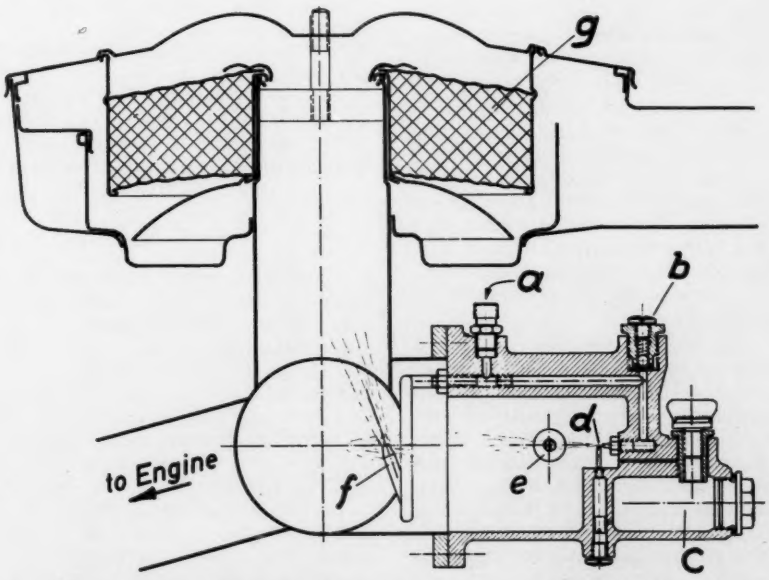

Figure 13. Cold starting device in intake manifold (a) compressed air inlet, (b) automatic pressure control, (c) fuel tank, (d) air and fuel nozzles, (e) spark plug, (f) secondary air nozzle, (g) metallic air filter insert.

THE MULTI-FUEL CHARACTERISTIC OF THE M-SYSTEM

As discussed previously, the successful elimination of combustion noise in the M-system is achieved by reducing to a minimum the portion of the fuel involved in autoignition. The rate of mixture formation is controlled by the temperature in the combustion chamber, i.e., by combustion itself, because it takes a rise in temperature to accelerate vaporization of the fuel film on the wall of the combustion chamber.

These two features of the M-system result in another remarkable advantage, in that they make it possible to operate on fuels having considerably lower ignition qualities than gas oil.

It is desirable to extend the fuel range of a compression ignition engine to include low-boiling fuels, such as gasolines and all kerosene fractions between the gasolines and the gas oils and so to obtain a multifuel engine which is capable of burning all distillation fractions with a boiling point up to 750° F.

Modern refining processes yield gasolines of a high octane number and correspondingly low cetane number. If such a gasoline is used in a diesel engine of the "air distributing" type, the combustion roughness will increase intolerably. The reason is that within the long ignition lag a large percentage of the fuel particles suspended in the air undergo the preparatory phases to autoignition so that, when the latter occurs in a favorable place, a small amount of energy is sufficient to cause a large portion of the fuel to react rapidly.

As a matter of fact, the M-system in itself does not reduce the ignition lag, but in the course of the longer ignition lag it allows only a negligible amount of additional mixture to form, since there is no temperature rise in the combustion chamber during that phase acting as an accelerating factor to the vaporization of the fuel on the wall.

The vaporization on the wall is speeded up only when the "air distributed" fuel portion has overcome the ignition lag and begins to liberate heat. And then the higher vapor pressures of the low-boiling fuels prove most effective in making up for the time lost due to the long ignition lag. For the subsequent combustion, it is actually favorable to have antiknock fuels because they are more likely to be ignited by the initial ignition particles before they ignite spontaneously.

The real problem in burning low-boiling fuels in the M-engine is in shortening the ignition lag adequately. This can be effectively solved by raising the compression ratio or applying supercharging.

Thus, a compression ratio of 1:19 will make it possible without any supercharging to use gasolines of as much as 80/86 octane while obtaining the same peak output. It even allows idling for many hours without misfiring or any audible combustion noise. It follows that such an engine is capable of operating on all other petroleum fractions with a higher distillation temperature than gasoline.

The performance data and specific fuel consumptions at the smoke limit for a large number of widely differ-

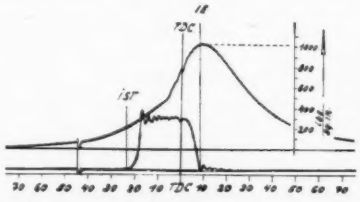

Figure 14. Output and specific fuel consumption of multifuel version of 6-cylinder engine, 4.4 in. bore, 5.5 in. stroke, with natural aspiration, for different fuels.

ent fuels are given in Fig. 14. Included are data for a lubricating oil of SAE 10 viscosity. Because of the great differences in the specific gravities and, therefore, in the heating values per unit volume of the fuels, it is necessary to adjust the injection quantity to obtain the same output. One fixed setting is, however, sufficient for the ignition timing without suffering much from the compromise.

It is a remarkable fact that the high octane gasolines, particularly in the low-speed range, give a better fuel consumption than gas oils. At high speeds, this relationship is reversed, because in that range the ignition lag of gasolines can be sufficiently shortened only by retarding injection to some extent. Best results are obtainable with the jet engine fuel J P 4. The table in Fig. 15 shows a comparison of the specific fuel consumption and mean effective pressures attained with 10 different fuels within the distillation range from 104° F to 752° F. Included are values for part load at the most economical rating and at a mean effective pressure of 35.5 psi. The two lower rows show the maximum and minimum brake mean effective pressures and specific fuel consumptions measured at the same exhaust discoloration of Sm = 60 per cent and at part loads. As can be seen from this comparison, the differences in the mep at 60 per cent exhaust discoloration become less as the speed is reduced. The reverse holds for the fuel consumption values which diverge, with decreasing speed, particularly at a mean effective pressure of 35.5 psi. Taking into consideration the widely different characteristics of the fuels tested, it can be said that the differences are not really significant. The multi-fuel capacity is emphasized by fuel No. 5 which, with a distillation range from 104° F to 752° F, contains all fractions that distill in the atmospheric tower of the crude oil refining process. The good results attained with this type of fuel prove that the engine is capable of operating on any mixture of the listed fuels. This enables the user of diesel power to operate most economically on any one of a wide range of distillation products.

THE INDICATOR DIAGRAM

In order to obtain distortion-free pressure diagrams, a cylinder head was drilled so that the diaphragm of the quartz indicator could be placed flush with the cylinder head, avoiding an additional clearance volume and indicator duct. A photograph of an actual diagram taken at 1900 rpm and 100 bmep is reproduced in Fig. 16. The injection begins, according to the needle lift diagram, 23.5° bTDC and ends after a period of 33° of crank rotation, 9.5° aTDC. The ignition takes place 7.2° bTDC after an ignition lag of 16.3° of crank rotation. There is a constant rate of pressure rise of 57 psi per degree of crank rotation up to nearly the maximum pressure which is attained 8.5° aTDC. The pressure curve is free from modulating pressure oscillations. (The break which interrupts the pressure slope was caused by the dead center mark). The peak pressure is 1020 psi for the injection timing resulting in the lowest consumption. If the injection is retarded four degrees of crank rotation, the peak pressure will drop to 920 psi; however, the fuel consumption and exhaust smoke deteriorate.

From the summary given in Fig. 17 of the results obtained from the pressure diagrams, it can be conclud-

No	Fuel	Specific Gravity °API	Boiling Range °F	% Residues + Evaporation Loss	Heating Value LHV / 18270	H %	C %	S %	Octane No	1900 RPM psi	lbs/BHP/hr Sm = 60%	lbs/BHP/hr Optim.	35.5	1400 RPM psi	lbs/BHP/hr Sm = 60%	lbs/BHP/hr Optim.	35.5	1000 RPM psi	lbs/BHP/hr Sm = 60%	lbs/BHP/hr Optim.	35.5
1	Commercial Diesel Fuel	38.3	372 | 680	1.5	1.001	13.03	86.01	0.72		113.8	.389	.381	.455	118.0	.378	.367	.464	118.8	.378	.363	.434
2	Gasoil 428 - 644 °F	38.0	414 | 644		0.9935	12.38	86.89	0.59		118.8	.401	.372	.459	121.0	.381	.372	.452	118.8	.383	.369	.436
3	Gasoil 392 - 572 °F	39.0	399 | 563		0.998	12.99	86.56	0.39	54	113.6	.383	.372	.452	121.0	.376	.367	.430	113.9	.376	.363	.430
4	Diesel Fuel Imported from Austria	33.4	399 | 698	4.5	1.002	13.27	86.66	0.08	52	100.8	.387	.385	.466	119.5	.385	.374	.461	113.9	.385	.378	.443
5	Special Wide Range Diesel Fuel 104-752 °F	39.0	104 | 745	2.5	0.982	13.30	86.16	0.66	41	108.0	385	380	463	114.8	.374	.365	.450	113.1	.376	.367	.434
6	Cracked Diesel Fuel	26.5	412 | 597	1.0	0.968	10.93	87.14	2.07	~25	110.2	.389	.385	.488	120.3	.385	.372	.461	120.3	.394	.378	.457
7	Diesel Fuel with High Sulphur Contents	36.0	363 | 662	2.0	1.005	12.74	82.25	5.00	46	111.9	.405	401		110.3	.385	.383		111.8	.394	.383	
8	Aramco Crude Oil (purified)	34.6	153 | 680		0.994	12.40	84.27	1.63	51	101.7	.405	.398	.481	110.0	.394	.385	.472	(98.1)	.387	.385	.464
9	Mogasoline 80/86	54.5	95 | 392(680)	2.0	1.018	13.70	86.10	0.21	~16	108.1	.362	.354	.423	118.1	.338	.331	.406	123.1	.346	.333	.394
10	JP4	51.5	131 | 549	1.0	1.022			0.16	~35	115.0	.376	.352	.416	118.1	.353	.340	.400	120.9	.367	.349	.397
	max. / min. } Values of Brake Mean Effective Pressure and Specific Fuel Consumption									118.8 100.8	.362 .405	.352 .401	.416 .488	121.0 110.0	.338 .394	.331 .385	.400 .472	123.1 111.8	.346 .394	.333 .385	.394 .464
										+4% -11%	+12	+14	+17	+3% -7%	+6	+16	+18	+4% -7%	+14	+15	+18

Figure 15. Results of multifuel tests, and fuel characteristics (60% smoke, i.e., exhaust just visible, giving limit for maximum mean effective pressure.)

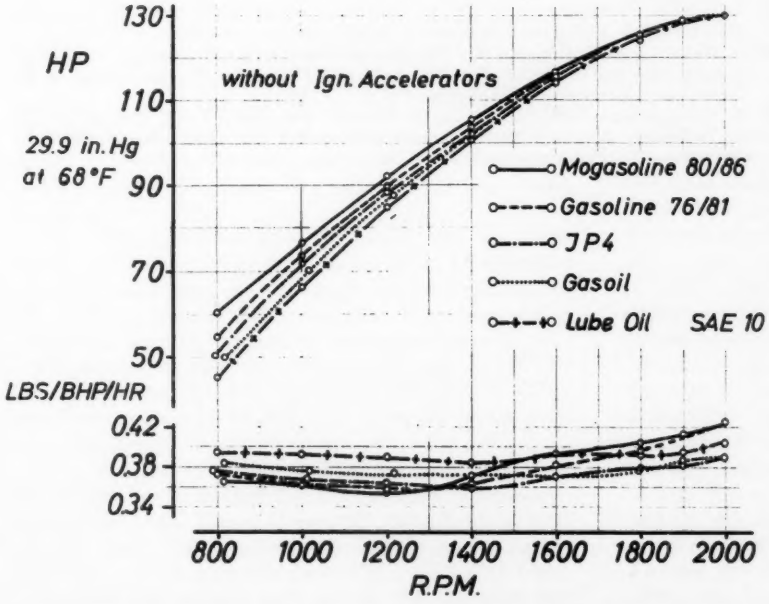

Figure 16. Pressure-diagram for 1900 rpm and 100 psi mean effective pressure.

ed that the rate of pressure rise required in the M-system to obtain optimum results is between 35 and 57 psi per degree of crank rotation. With increasing speed, the higher rate of pressure rise has to be accepted. The maximum combustion pressures are dependent on the mean effective pressure and the speed. They range between 840 and 1020 psi according to the speed for a mean effective pressure of 100 psi.

In order to ascertain the source of the combustion noise which is audible outside the engine, the transmitted sound was recorded, together with the pressure in a manner that the sound modulates the pressure curve. In the M-system, no increase in the noise amplitude is found after ignition and the beginning of combustion, and only at the moment of maximum pressure does a sound modulation appear. Quite contrary to the M-system, in the "air distributing" engine the maximum amplitudes of the sound modulation arise immediately

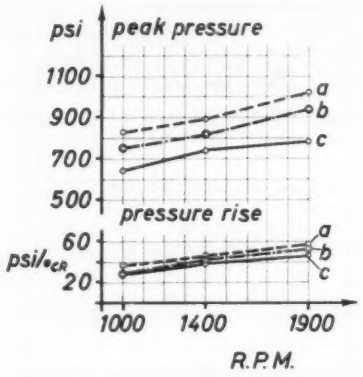

Figure 17. Peak pressure and pressure rise in relation to speed and mean effective pressure. (a) mep 100 psi, (b) mep 77 psi, (c) mep 46.5 psi.

after ignition and before the steep pressure rise is completed. This suggests that the source of sound is not only in the rapid pressure rise but that, similarly to the gasoline knock, the high rate of pressure rise is accompanied by pressure waves of high frequency, which hit the wall of the combustion chamber and cause the metallic sound of diesel knock.

An interesting test elucidating the ignition phenomena in the M-system can be made by relieving the spring load on the nozzle needle with the engine running so that the nozzle opening pressure becomes zero. The same amount of fuel is injected into the cylinder as before, but the pressure, particularly at the beginning of injection, is lower so that no fine atomization takes place in the first phase of injection. Consequently, there is no self-igniting fuel fraction as it is required in the M-system for pilot ignition and in spite of the fact that fuel is injected, the charge must fail to ignite.

Actually, this can be observed at speeds up to about 1800 rpm even if the above test is made with maximum mep and, therefore, maximum temperature in the combustion chamber. At higher speeds, the effect is not quite so clear because the fuel velocity becomes high enough to form a small amount for initial ignition although rather late.

CONCLUSION

The evaluation of reaction kinetics as discussed in this paper has led to the M-system. The first realization of the M-system in the MAN truck diesel engine suffers still from some compromises, shows, however, clearly the following advantages over conventional combustion systems:

1. The diesel knock can virtually be eliminated even at very low speeds, resulting in a quiet engine with an extremely elastic torque characteristic.
2. Engines with the M-system can be operated as true multi-fuel engines on a widely different range of fuels from gasoline over jet fuels to diesel fuels without sacrificing engine performance.
3. The M-system combustion produces less soot per pound of fuel than conventional systems at part load.
4. The path of reactions in the M-combustion system is similar to that in gasoline engines with the result that lube oil contamination is no greater than in gasoline engines.

REFERENCES

1. J. S. Meurer, Neuere Mittel zur Untersuchung der Vorgänge im Motor. Bericht der VDI-Jahreshauptversammlung in Darmstadt 1936.
2. J. S. Meurer, Das neue MAN-Verfahren für schnellaufende Dieselmotoren. ATZ (Automobiltechnische Zeitschrift) 1940 No. 8.
3. K. Numann, Fortschritte in der Erkenntnis der Dieselmotorischen Verbrennung. Schriften der Deutsche Akademie der Luftfahrtforschung 10./11.5.1939.
4. S. Arrhenius, Zeitschrift für physikalische Chemie Abt. A Vol. 4 (1889) p. 226.
5. B. M. Sturgis, Some Concepts of Knock and Antiknock Action. SAE Journal December 1954.
6. M. A. Elliot, Combustion of Diesel Fuel. SAE Quarterly Transactions Vol 3, July 1949.
7. K. Neumann, Kinetische Analyse des Verbrennungsvorganges. VDI-Forschung Vol. 7 (1936).
8. G. Beck and Ch. Erichsen, Spektraluntersuchung des Verbrennungsvorganges. VDI-Forschsungsheft 377.
9. J. Ulsamer, Wärme-Übergang von Drähten an strömende Luft. VDI-Forschung Vol. 3 (1932) p. 34.
10. K. Karde, Beitrag zum Verbrennungsvorgang in der Dieselmaschine. ATZ (Automobiltechnische Zeitschrift) 1936 No. 20 p. 501-515.
11. P. Rieppel, Versuche über die Verwendung von Teerölen zum Betrieb von Dieselmotoren. VDI-Forschungsheft 55 Berlin 1908.
12. C. Wollers und V. Ehmcke, Der Vergasungsvorgang der Treibmittel, die Ölgasbildung und das Verhalten der Öldämpfe und Ölgase bei der Verbrennung im Dieselmotor. Kruppsche Monatshefte Vol. 2, p. 1 1921.
13. W. Wentzel, Zum Zündvorgang im Dieselmotor. Forschung Vol. 6, 1935 p. 105–115.
14. O. Holfelder, Zündung und Flammenbildung bei der Diesel-Brennstoff-Einspritzung. VDI-Forschungsheft 374 (1935).

CHIEF MACHINIST JOSEPH E. SCHIRMER, USN

"THE NAVY'S FIRST COMBUSTION CONTROL SYSTEMS"

THE AUTHOR

This is the author's third article for the Journal. He has worked with combustion controls on naval vessels for the past 5 years, teaching controls for the Navy and has engaged in free lance writing for the past 10 years on controls and boilers. Served as boiler officer aboard the USS Northampton (ECLC1) for 28 months and is presently attached in the same billet to the USS Forrestal (CVA59). He is preparing a book on automatic combustion controls which he hopes to finish within another year.

FOR MANY YEARS, the merchant marine has used automatic combustion controls, and has long since proved the economy and efficiency derived from the use of these controls.

The Navy has been rather slow in accepting and using combustion controls, and it is just within the past decade that they have finally applied these controls to combat vessels. While the USS *Robinson* (DE220) was the first combat ship to have controls installed aboard, it took approximately five years before controls were installed aboard a first line combat ship of the fleet.

The USS *Northampton* (ECLC1) was the first large combatant ship with automatic combustion controls installed, and through the evaluation of the controls aboard this vessel, the Navy has finally accepted them for all major combatant vessels.

Up until the *Northampton* installation, the Navy had approximately two hundred and fifty-three (253) auxiliary vessels of 19 different types equipped with these controls.

The US Naval Boiler & Turbine Laboratory at Philadelphia conducted the first test on combustion controls in 1940. Hagan Company controls were used for this test, and resulted shortly thereafter in installing a set of controls aboard the USS *Robinson*. Complete test results and agenda for this test are contained in NBTL test No. 2272B.

The first controls were installed on a "D" type boiler with integral type superheater designed by the Boiler & Turbine Laboratory. This boiler had an operating pressure of 435 psi with a total steam temperature of 740 degrees F.

Figure 1 shows the schematic of this control drawing, which in its relative simplicity, bears no need for further explanations.

Little if any data can be found in the Boiler & Turbine Laboratory's files on the performance of these controls aboard ship, and for that matter, on any other tests pertaining to controls. However, the controls apparently showed enough promise because another series of tests were started in February of 1948.

NBTL Test No. B14, conducted from 2 February through 29 November 1948 brought forth the first set of controls to be installed on the USS *Northampton*. This time Bailey Meter Co. controls were used, and through close and complete cooperation between Laboratory and manufacturer's personnel, the controls tested satisfactorily and were installed aboard the *Northampton*.

This test employed a Babcock & Wilcox "M" type boiler, divided furnace, separately fired and controlled superheater with a Todd "L" type atomizer. During the time from 20 April through 30 October 1948, test No. B14 (1) part 1 was run employing the same boiler and controls, but using the Return Flow

10 type Babcock & Wilcox burners. These latter burners were eventually installed on the USS *Northampton*.

While the above tests were being conducted, part 2 of Test No. B14 (1) was being conducted on the Bailey Meter Co. 2 and 3 elements feedwater regulators. These regulators employed an electronic flow transmitter with a thermo-hydraulic single element emergency system.

The 3 element regulator was installed for use with the controls on separately fired superheat controlled boilers, and the 2 element regulators were used on single furnace integral type superheat boilers. The single element regulator proved unsatisfactory for the units being tested. It is to be noted here that 2 element control is the minimum standard for Navy boilers.

The 3 element regulator proved highly satisfactory and is a far cry from the old "Belleville Boiler automatic feed control" which consisted of a chamber with a float which varied with the water level and depended upon an almost friction-less movement of a spindle in a packed gland.

The author had the pleasure of working with the controls aboard the USS *Northampton* for the first 28 months of their life. During this evaluation period, it was surprising how little actual maintenance was required; how quickly the enlisted personnel gained confidence in the controls and mastered their operation, and what few problems if any, arose from the controls.

The only major problem encountered with this first installation was poor air—oily air which is the nemesis of any control system. This was eventually remedied by the installation of better compressors.

The instruments required very little if any replacement of parts, and the only replacement parts required in the electronic gear was an occasional peanut tube.

It is rather unfortunate that at this writing, security regulations prohibit a complete description of the control system aboard the USS *Northampton*. I am certain that any marine engineer, especially those interested in control systems would find this system rather interesting and a challenge to his ingenuity.

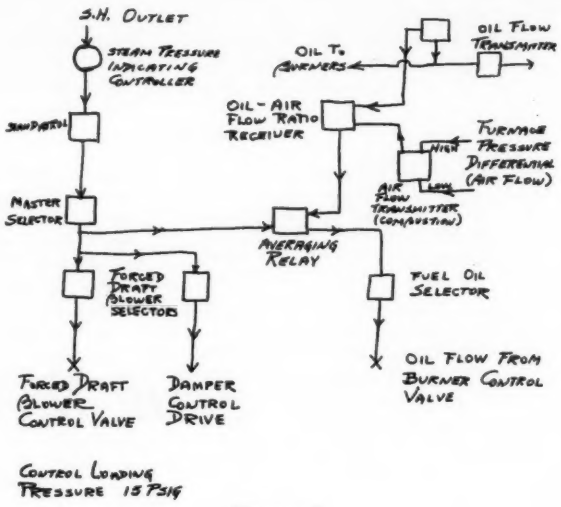

Figure 1

While the Navy has been slow and at times a bit reluctant to accept automatic controls, it has come a long way in the past few years as evidenced by the *Northampton* installation and further amplified by the installations aboard the USS *Forrestal* and *Saratoga* with which the author has had the pleasure of working.

Automation with marine boilers has arrived, and it should be the fond hope of every marine control engineer of eventually seeing marine boilers controlled completely from the bridge through the medium of automatic combustion controls.

ASTRONAUTICS IN THE UNITED STATES

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THE SCIENCE of space flight finds itself today in a rather odd predicament. Having survived an infancy beset by attacks and ridicule, it now stands more or less at the "cross-roads" of decision. The question has practically ceased to be "Shall we fly in space?" But rather "How shall we do it?" A number of unexpected paradoxes and dilemmas complicate the problem of reaching a decision. Public and technical opinions of the field in some ways are, strangely, almost too favorable. The technological disciplines needed for the conquest of space exist but are largely inaccessible because of military security. But, even ignoring the security problem, there appears to be a profound difference of opinion among top scientists regarding the number and type of steps to be taken. The good and bad features of the situation tend to cancel each other out to a certain extent, making a clear assessment very difficult indeed.

In the realm of public opinion, for example, the advent and rapid development of radar, atomic energy, and rocket technology have often led laymen to the happy conclusion that "science can do anything." This sort of indorsement is both an asset and a liability to the scientist. As an asset, it means that a taxpayer is willing to help finance astronautical research; its liability lies in the fact that a layman, too-easily sold, can become just as easily disenchanted by expecting too much too soon. Since the sheer magnitude of the undertaking of space flight makes it almost inescapably a governmental affair, the climate of public opinion is no trifling matter.

The well-meaning lay enthusiast too frequently fails to recognize the appalling stature of some of the technical problems still to be worked out, and falls easy prey to careless "Sunday Supplement" journalism, misinterprets military censorship, or, worse still, gets taken in by occasional calculated deceptions by publicity-seekers. The "flying saucer" may be regarded as a symptom of the layman's frustration and confusion. The public mind, having finally wearied of ridicule, is now beginning to shift its viewpoint. It develops a growing yearning to see a space ship. Phenomena which would have attracted only brief attention in past years are now marshalled with a somewhat religious fervor by saucer protagonists to prove their point. For a time, the flying saucer question seemed susceptible to some sort of legitimate investigation, but with the appearance of some recent books on the subject, it does seem, in the words of Macbeth, that "Confusion now hath made her final masterpiece!"

The existence of military secrecy is both a paradox and a dilemma. Weapons engineering has brought rocketry to a rather high state of development, but it is now, by virtue of its secrecy, beginning to isolate itself from the type of thinking that gave rocketry its origin of systematic study in modern times . . . space flight. Not that space vehicles could not be weapons, but applied science, in its headlong rush to get things into the hardware stage ahead of competitors in the same field, inevitably loses much of its contact with the theoretical disciplines, without which it will even-

tually grow barren. Military secrecy, however noble its motives, nonetheless compounds this sin by throwing up a barrier which cuts off information going the other way. It doesn't take a scholar to see that this must be remedied or both camps will starve to death intellectually.

Now it's probably clear, even to a very casual observer, that the achievement of space flight will require fantastic sums of money . . . sums which would strain the budgets of the largest of nations. The obvious solution is global collaboration, but this, unfortunately, requires not only a utopian level of world peace but a rather improbable popular espousal of scientific knowledge for its own sake.

Last spring, Dr. Walter Dornberger, formerly Commanding General of the Peenemunde Rocket Test Station and now Missile Design Consultant for Bell Aircraft, pointed up the military paradox in connection with a discussion on global collaboration as an alternative to individual national bankruptcy. He feared it must always remain a dream. Worse, it is likely that only military reasons can ever muster such vast sums. Private individual or corporate research are indeed commendable but stand little chance of making important contributions. Dr. Dornberger praised the realistic thinking of Mr. A. V. Cleaver (British Interplanetary Society) and expressed a 95% agreement with a paper presented by that gentleman in 1953, "A Programme for Achieving Interplanetary Flight".

He summarized three phases outlined by Mr. Cleaver:

Phase I Theoretical and applied work resulting in the establishment of an unmanned satellite.
Phase II Operation of a regular manned satellite, and some occasional circumlunar flights, and
Phase III Landings on the Moon and planets and return.

"Phases I and II," he said, "could be defended on the basis of military advantage. But Phase III would be difficult to "sell" to the tax-paying public on any grounds. What possible practical advantage could you demonstrate?"

Dr. Dornberger went on to show how the wide currency of this argument of military advantage throws up a formidable barrier between the practitioner and the theorist. The practitioner deals with hardware and is walled about by secrecy. This secrecy frustrates the theorist, whose lot is hard enough even with adequate practical data, and he must content himself with topics which in many cases must strike the casual observer as academic minutiae. This situation is not likely to change for a long time but he feels that the theorist could well and profitably make a virtue of necessity. Taking this undesirable information vacuum at face value, the theorist could jump ahead, say 30 or 50 years, and perform many valuable studies from the viewpoint of space flight as a fait accompli . . . such problems as, perhaps, interorbital transport, space navigation, solar power generation and microclimatology in space vehicles.

The American Rocket Society empaneled an "Ad Hoc Committee on Space Flight" in 1952. The final report of the Committee, published in November of that year, suggested both optimism and caution. The optimism was implimented by recently making the Committee a permanent affair. Even more recently this Committee recommended to the National Science Foundation that a study of the utility of an unmanned Earth satellite vehicle be made. The caution is indicated by the chairmanship of that Committee, which was invested in the person of Mr. Milton W. Rosen, Director of the United States Navy's Viking Project. Mr. Rosen is as anxious to see the conquest of space as anyone you can name, but after having launched about a dozen Vikings he can tell you that the number of things that can go wrong with a rocket is simply horrifying.

Optimism and caution are important ingredients of any philosophy of action. In any mature philosophy, they are present in approximately equal amounts, perhaps in exactly equal amounts, and in the latter case they do not necessarily neutralize each other. Mr. Rosen, in effect, says, "we can do it, but let's be careful." Dr. Wernher von Braun, scientific director of the V-2 project at Peenemunde, and now Guided Missiles Technical Director at Redstone Arsenal, Alabama, has, like any engineer, a solid respect for a margin of safety. But he also knows from experience that technological caution is easily misconstrued as doubt by the lay mind. In this light, a recent statement by Dr. von Braun, says, in effect, "Let's be careful, but we can do it." Consider the following:

The feasibility of flight through outer space is no longer a topic for academic debate. High-altitude rockets have repeatedly risen beyond the upper fringes of the atmosphere and have shown that rockets can be propelled and guided through the atmosphere to outer space. Even animals have been carried aloft in such flights and they are in as good a state of health today as they have ever been before.

From the engineering aspect, manned space-flight, and its ultimate purpose—voyages to the Moon and nearer planets —are merely a logical extrapolation of the present art of rocketry. Admittedly it is a bold extrapolation: The Moon ships of the future will compare to the present day high-altitude rocket as a modern airliner compares to a bail-and-wire aeroplane of 1910. The same ingredients are required to make space flight as successful as aviation: Devotion on the part of its protagonists, money, and a determined step-by-step program.

Research will play a vital part in Man's imminent conquest of space. It will have to provide answers for many still-open questions, not only in the realm of engineering, but even more in adjacent fields, such as aviation, medicine, radiology, meteor research and others. In a revolutionary technological endeavor—such as aviation was years ago, or as astronautics is today—these supporting sciences involved have to fight for their recognition and respectability. Thus it is hardly unusual that we space-flight protagonists are occasionally frowned upon by members of the older scientific fraternities. We should not bother about this, however, for the younger scientific generation is on our side. The time is here when it is no longer possible to argue the feasibility of commercial aviation. Soon the time will come when it will no longer be respectable to raise doubt at the feasibility of Astronautics.

This is not particularly at odds with Mr. Rosen, for Dr. von Braun has also launched a few rockets and also knows that a rocket is subject to an exasperating variety of failures. What throws some of us off the track is the sense of mission in von Braun's philosophy, which arouses a vaguely uncomfortable recollection of some of the biblical prophets. This is because many of us are subject to a sort of planetary provincialism. Having no inkling of the stupefying immensity of the sidereal Universe, we cling subconsciously to the notion that we and this planet somehow dominate the scheme of things. Mr. Rosen has no illusions in the matter. He simply elects to keynote another important aspect of the over-all problem.

It would be well to dwell for a moment on von Braun's sense of mission. Those who do not grasp it may well wonder what all the fuss is about. Rockets rise to higher and higher altitudes with comforting frequency, and the Moon, being plainly visible, seems quite nearby. The fact of the matter is that new altitude records are extraordinarily hard to come by and 238,000 miles vertically is quite a distance. The distances to the planets range between 30,000,000 and 4,000,000,000 miles. The distances between the galaxies is almost beyond comprehension. Realization of what all this means will have a shattering impact on the human race. If the layman is not introduced to all this by gentle steps, through a sort of advance public relations, he will most assuredly lose heart and withdraw his support when the magnitude of the situation dawns upon him. This would be as tragic as it is unnecessary. All that is required is to introduce the people gradually to three-dimensional space. Someone has to do it . . . and thus far von Braun appears to be the most articulate voice.

Mr. Kurt Stehling, Rocket Research Engineer for Bell Aircraft Corporation, feels that with the present missile program underway in the United States, the problem of orbital and space flight will be approached in one or several of the following ways:

1. As an outcome of the current missile program, at a time when the military requirements for missiles will be reduced.
2. A multi-service military project parallel with the missile program.
3. Less likely, a special agency, like the AEC, established for the purpose.
4. Least likely, a program undertaken by a group of private industries or foundations, and who will bear all or most of the financial burden.

The problem arises as to which facility or group of facilities may construct the vehicle intended for the above purpose and what type of personnel will be responsible for the enterprise. Since methods of approach have a way of being influenced by the personalities involved, it would be worthwhile to note his assessment of the more significant groups:

1. The technicians and scientists who were formerly enemy nationals (mostly Germans) and who have come to this country have often been leaders in urging the beginning of a space flight program and have shown some remarkable technical aptitudes and experience in the field of rocket propulsion. Many of these men are in positions of trust and responsibility in the missile industry of this country, and, as, such, influence the functions and details of a space flight program. However, because of their former national background, and sometimes anomalous positions as citizens or non-citizens, and often lack of political connections, they suffer from a handicap when the ultimate decisions must be made. They have a natural inclination for such projects after having worked for the Nazi war machine for many years. However, they are sometimes not fitted for interpreting our missile program to the American people, and have to be very careful not to show a sense of impatience with the democratic processes and fine points of good public relations. To sum up therefore, the technical influence of these people is considerable, but their political and managerial influence tends to be of a lower order.
2. The second group of people in the United States who will influence space flights is the existing body of designers, engineers, and managerial personnel who have been in the aircraft business for a long time and whose outlook is definitely less influenced by unreasoning haste and impatience, to the disadvantage of space flight. They tend to be more cautious, especially when they have to regulate the activity of large defense or industrial establishments. However, these managerial and leading technical men (who are often more mature) will play a very important role in guiding and supervising the activities of the younger engineers, and in selecting from these younger people those whom they feel will most capably guide future projects such as space or orbital flight. Their influence, then, is a very powerful one, and, if space flight is achieved within the next few years, a most crucial one.
3. The third large personnel sub-division may be grouped as the younger engineers and physicists who are just beginning to make a mark in the jet propulsion and rocket field. These men will tend to end up in the managerial and supervisory positions when these become vacant by the retirements of the men in group 2. This young group of men tends to be impatient with the objectives of the missile program and often minimizes the great technical problems which will be encountered, although they are not unaware of them. It is rather that this group is not as politically cautious as the older men, and can often outstrip the slow moving pace of public opinion. Nevertheless, this group with its technical background and often-considerable enthusiasm will make its weight felt increasingly in time, and, as such, will probably become the most important single technical group in any space flight program.
4. The last, but not least, important group consists of the young students in universities and even in the high schools who are the most idealistic of all and who often feel that space flight either should be or is "just around the corner." It is the duty of those elder technical people who have shown an interest in space flight to foster this enthusiasm in various ways so that some of the zeal will be guided over into the professional life of these students when and if they enter industry.
   A small subdivision of this group consists of the tiny but growing segment of scholars and teachers at the various educational institutions of this country who, often because of their less compromising connections, can speculate on the various aspects of space flight, and who often treat this subject in a rigorous and scholarly fashion. This approach is difficult for men in industry who are busy with the many ramifications of their jobs.
5. The most important group of all is the American voter and taxpayer who must ultimately pay for any project of this type. It need only be said that the enthusiasts of the four preceding groups can do much good by approaching the subject in a calm and dignified manner, and in interpreting the benefits and possibilities of space flight as objectively as possible to the public which may be in a serious questioning mood, especially if budget limitations and increasing taxes are a factor in the country's economy.

As it is just not in the nature of things for any one of these segments, noted by Mr. Stehling, to be in complete command of the situation, the way or ways in which space flight will be undertaken will ultimately be the result of a blending of the influences of these various groupings. Astronautical men recognize three general schools of thought. The first is that which proposes a frontal attack of the problem of space flight by attempting a direct flight to the Moon, or, at least, the early establishment of a manned satellite vehicle orbiting around the Earth. The second is more cautious, and feels that the most logical intermediate step is to establish unmanned satellite vehicles in rather modest orbits which will observe Earth, space and the various celestial bodies, and relay information back to ground stations by means of telemetering equipment. The third group, most cautious of all, distrusts the fearful complexity of automatic and electronic equipment, and thinks that the probability of malfunction is prohibitively high. This group feels that space flight is best achieved by gradually extending the performance of present vehicles, under human control, so that scientific phenomena are under immediate intelligent observation at all times, and that, in the event of malfunction, there is a good chance that the expensive vehicles may be salvaged for study and improvement.

Only time will tell which school of thought finally makes its philosophy of space flight most felt. The best that can be said at this moment is that, although the over-all astronautical situation is beset by a formidable complex of technical, personal and political problems, the basic ingredients of the conquest of space are now finally at hand, and Man, being what he is, is not likely to rest until he has made that conquest.

The new miniature gyro-compass, designed for use on small naval craft, occupies less than one-half cubic foot of space, and because of its simplicity can be operated by Navy men without specialized training.

* * *

There are more than 7 million items used in the construction of the complex modern submarine.

LIEUTENANT-COMMANDER Y. ROLLOF
Royal Swedish Navy

CONSTRUCTION OF WEAPONS

THE AUTHOR

graduated from the Royal Swedish Naval Academy in 1937 and served in various types of ships until 1942 when he received post-graduate instruction in common and high gunnery for two years. He served in the Naval Administration and then attended higher courses at the Royal Polytechnic Institute until 1948 when he became Gunnery Officer of the Cruiser Gotland. He was Chief Naval Inspector in Bofors in 1949 to 1952 and graduated from the Royal Polytechnic Institute as a metallurgical engineer in 1952. The following year he commanded HMS Ehrenskold. He is now head of Naval Ordnance Inspection at Naval Administration.

"We strain at the gnat of perfection
and swallow the camel of unreadiness"
(LORD FISHER)

THERE WAS A TIME when military change was a slow "historical" process. Lord Nelson's flagship at Trafalgar was forty years old and good enough for the job; the modern airplane has an obsolescence cycle of about four years. Nowadays it is a difficult problem to keep a country's defense at the peak of technical efficiency.

It is, therefore, of the greatest importance that the development of weapons is considered from the right point of view in order to ensure the proper use of funds placed at the disposal of the military administration. If it were possible to know when the material would have to be ready—(in fact to know when war will break out)—it would be easier to choose the weapons. Since it is the attacker who decides on the date for attack and as we—as defenders—do not own a magic crystal ball in which we can see the future, we must always be on our guard. The long terms of delivery of modern complicated weapons greatly increases the problem of war-preparedness at short notice. Sir Winston Churchill once said that with weapons it is always the same thing, the first year we get nothing, the next year merely a trickle and the third year a rapid river.

SORTING OUT OF PROJECTS

It is important to sort out low priority projects in order that research and development teams can concentrate on vital items.

The problem is to decide which weapons are absolutely necessary to win battles and which weapons are mere idle wishes which could never be designed and, even less, manufactured on a large scale at a reasonable cost.

The U.S. approach to weapons design reminds Rear Admiral Malcolm F. Schoeffel, Chief of the Navy's Bureau of Ordnance, of the White Knight in "Through the Looking Glass" from "Alice in Wonderland." Alice had asked the Knight why he kept a mousetrap on his horse's back. "It isn't very likely there would be any mice on the horse's back." "Not very likely, perhaps," said the Knight, "but if they do come, I don't choose to have them running all about." "You see," he went on after a pause, "it's as well to be provided for *everything*. That's the reason the horse has all those anklets round his feet . . . to guard against the bites of sharks." To prepare against various other contingencies, the White Knight also

carried a beehive, a bag of candlesticks, a set of fire irons, bunches of carrots, and "many other things."

"If the White Knight were to ride through the Pentagon today," one wag has suggested, he could scarcely escape without "a radio direction finder, scanning radar, retractable wheels and tractor lugs, bulletproof vest, entrenching tool, a small battery of free rockets, automatic pilot, ejection seat, dual wiring systems, Silex coffee maker, a T-47 .30 caliber automatic shoulder weapon, a can of napalm, oxygen mask, pair of dark glasses, and a pair of Shoes, Field, Personnel."

It is necessary to estimate the likelihood of such-and-such an equipment coming into use in a war. The famous American scientist, Dr. Vannevar Bush, considers that officers do not distinguish often enough between the 1 in 50 chance that a certain equipment will come into use and the 1 in 5000 chance. In a war it is more important than in peace to save men and material and to concentrate on the essential questions —what is essential depends largely on the one who is speaking and who is deciding. With the aid of a thorough weapon analysis it is, however, possible to form an appreciation on which to base judgment.

Before initiating the design and manufacture of a new weapon, the following questions should be answered:

(1) *Can the weapon be expected to offer any new advantages. Are the calculated advantages so big that they justify the work of a new design?* Development and production of a less useful weapon draws labour from more important projects. Before an industry in peace-time introduces a new product a thorough investigation of the potential market is made in order to judge whether production is worth while. Before construction and manufacture of a new weapon the same careful investigation should be made. Will the production of the weapon have a chance to inflict sufficient damage on the enemy to outweigh the resultant economic losses in men and material which might have been used to better purpose? In military staff requirements in peace-time a certain price limit is set and the problem is to choose between different weapons, since it is impossible to acquire all of them, especially nowadays when the cost of weapons has risen enormously and there are so many from which to choose.

The ever increasing technical nature of war requires a more intimate team-work between military personnel and non-military scientists. One should neither forget the advice of the "user" of the weapons nor the psychologist, so that the material will be constructed in a practical manner and adapted for "normal" people. According to American information the German Air Force's research and development of weapons during World War II was organized in an exemplary manner, particularly in comparison with the Army and the Navy. The Air Force achieved this partly by employing the most skillful scientists to whom they gave privileges and advantages, the essential quiet for work and the possibility for stimulating contacts between different groups of scientists; and partly by using a good staff of technicians who could judge the practical possibilities of any project. The Army on the other hand was conservative and unwilling to try new methods (except in tanks and rocket projects) and was largely in the hands of the important private armament manufacturers. This was forcibly demonstrated in the sphere of ammunition production where the suppliers were content with small modifications to old designs. In this way private firms made considerable profits with little outlay on expensive research. If the Army itself had carried out the research on a large scale, it could have affected the development of weapons in a way more favorable to the fighting forces. Due to lack of team-work and contacts between the different authorities and research groups concerned, unnecessary duplication occurred in many cases.

(2) *Is the proposed construction program possible to execute?*
A weapon can be designed on a simple theoretical principle but in spite of this the mechanical solution can be extremely difficult. The practical solution of a given weapon is in general a compromise of the original theoretical specification. All designs contain a number of adjustments between conflicting demands, e.g., for a gun-muzzle velocity and length of life. If one demand is stressed too much, another will suffer. Compromises are always dangerous and before the design of a weapon is definitely decided, it has to be "mangled" by the interested military authorities, the manufacturer, and the scientists. It is then particularly dangerous if the military demands are unreasonable and contrary to what is physically and technically possible. Military requirements decide what weapons we shall strive for but the standard of technique decides what can be achieved.

In the United States the expression "Christmas tree planning" is used to express the tendency to try to add as much as possible to a weapon. Everybody wants to hang something on a Christmas tree and it doesn't matter how much it costs or what it looks like when ready. This or that device is considered to be absolutely indispensable and the result is that the weapons multiply, the costs increase, the times of delivery lengthen and the necessary crew required grow larger.

In the American magazine Fortune (April 1952), the construction of the Submarines of the Killer class were given as an example of "Christmas tree planning."

The original intention was to build a couple of small submarines to be used for hunting enemy U-boats in submarine waters. By accepting a small radius of action and concentrating on one

kind of target, the Submarine was to have a displacement of only a few hundred tons and be suitable for mass-production. During the constructional work the Submarines finally grew to 765 tons, and had instead of an estimated crew of 10 to 20 men a final complement of 5 officers and 42 men. The Submarines, of which three were launched in 1951, are so full of technical equipments (including the inevitable ice-cream machine) that there is room for just four torpedoes in the forward torpedo-room while four others have to be kept on deck. On account of the complicated electrical equipment fitted, these boats cannot be built in an ordinary ship-yard but only by such specialists as the Electric Boat Co. Each Submarine is estimated to cost 10 million dollars.

(3) *Has the manufacturer got sufficient means for production of the weapon so that it will be produced in sufficient quantity within a reasonable time?*

It is important to give priority to the most paying project not only for the supply of raw materials but also to make available the machines and the labour. It is often necessary to use several manufacturers to produce a single weapon. The problem is then to ensure that the tasks are suitably distributed among the firms and that the purchaser has a good survey at all times of the state of progress by different sub-contractors in order that he may take the necessary steps to avoid "bottle-necks."

COMPLEXITY

The number of components in a complete modern weapon design is often frighteningly large. According to the theory of probability the reliability of the whole system is a product of each (quite independent) component's reliability. In a system with 100 separate important parts, each with 99 percent working reliability, the total reliability of the whole system is only 36 percent! It is obvious that in a complicated weapon each component's individual reliability must be considerably larger than the working security acceptable for the whole system.

Before the U.S. Navy permitted mass-production of the proximity fuze, (which consists of some 40 different parts), 50 percent overall working reliability was stipulated. This figure seems small but it must be remembered that even with this low working reliability the new weapon could increase the efficiency of the heavy anti-aircraft guns 5 or 10 times and the U.S. and British Navies urgently needed such an improvement. One of the most important maxims for developing the proximity fuze therefore was "We don't want the best, we want the first."

When manufacturing a complicated weapon the difficulties and costs of development, production and control will increase considerably with a number of components involved.

The complexity in general depends primarily on the demand for high performance. A new equipment could be simplicity itself. The complexity often arises when the original design must be changed in order to mount newer equipment. There is always a weight and space problem which is difficult to solve. The weight "merry-go-round" may lead to changes which from small beginnings lead to unexpected consequences.

It is important to ensure that weapons do not become unnecessarily complicated on account of a bad design. There is occasionally a dangerous tendency among designers to complicate the weapon unnecessarily by attempting to perfect the mechanical solution of a theoretical function. This may lead to the design being impracticable, particularly as the designer may not be familiar with the conditions under which the weapon is to operate.

The first solution of a design is generally complicated. The brilliant and simple constructions are mostly achieved after long and persevering work.

New weapons with high performances need not always be complicated. The land mine and the bazooka are examples of this. The latter combines the rocket principle and hollow charge in an extremely simple way.

The bazooka also shows the possibility of manufacturing a weapon rapidly in mass-production. In the North African Campaign new weapons were needed for an anti-tank role. After only three weeks of experiments, constructional drawings and tools for an acceptable weapon were made and a month later the weapon was in series production.

It is true that both the land mine and the bazooka are typical close combat weapons which in general can be simpler than weapons for long-range fighting. When it comes to action at long range, heavy demands are made upon accuracy which in general requires complicated devices.

A complicated weapon is often ordered in components from different manufacturers. To ensure correct functioning when the weapon is finally assembled an intimate team-work is necessary not only between the military command and the different manufacturers, but also between the latter. Representatives of the purchaser should be present at important discussions between the different manufacturers. A weapon should, however, if possible be ordered from only one manufacturer.

In spite of the fact that modern weapons take a long time to produce and because servo and electronic equipment are sensitive and difficult to handle, it is not an argument in favour of discontinuing the development and demanding a retrograde step in favour of a return to weapons out of date, or as Fortune says: "There are always pensioned officers who condemn all new-fashionednesses in the Army and recommend regression to the bayonet."

Even though the simpler short range weapon may of necessity be forced into production before the newer weapons are ready, it is not advisable to stop striving after the newer ones.

INSUFFICIENT TRIAL OF NEW WEAPONS

The sanctions resulting from insufficient trials of new weapons which later in war prove faulty differ

from ordinary peace-time articles in that the latter, in general, cost only money, while the former may cost men and, in the worst cases, may even lose one the Battle.

The Royal Navy's heavy armour-piercing shells during the first World War are an example of this. Lord Chatfield, Gunnery Officer and Captain of the flagship Lion, tells us in detail about the insufficient trials of the shells in his memoirs "The Navy and Defence." After the battle of the Dogger Bank suspicion was aroused that all was not well with the battle-cruiser's ammunition but the Admiralty assured the doubters there was no reason to doubt that the shells were the best in the world.

After the Battle of Jutland suspicion was further increased when the German battle-cruisers, in spite of a large number of hits (Seydlitz received 40 hits before it sank outside Wilhelmshafen), could still float, while the British Battle-cruiser Queen Mary was destroyed in the first salvo to score a hit. It was then that Admiral David Beatty said: "There seems to be something wrong with our bloody ships today."

The fault was in the one case due to insufficient flash-protection for the magazines and in the other the heavy armour-piercing shells which did not function on oblique impacts and which had a charge of lyddite so sensitive that it detonated on impact against relatively thin armour and not inside the ship.

Subsequent investigations proved that the Ordnance Department (due to shortage of ammunition after the battle of the Heliogoland Bight) had accepted armour-piercing shells which had not passed the stipulated delivery tests. Not until April 1918 were the most important fighting units compensated for a third part of the investigation's armour-piercing shells.)

Unsatisfactory material breeds mistrust among the personnel which causes a further reduction in efficiency.

TRIALS WITH PROTOTYPE

In order to decide how a new weapon will function, extensive tests must be performed which are carefully devised and well prepared.

Trials in detail from which the weapon's performances can be judged should be performed at an early period so that the prototype of the weapon will correspond with the requirements given in the design program. A number of specimens of the prototype should be manufactured simultaneously, particularly where destruction tests are necessary as in the case of ammunition. It must be possible in order to gain time to start production in series immediately after testing the prototype. Important modifications to a prototype requires a second prototype and hence longer terms of delivery.

When a prototype has been manufactured great care should be devoted to the planning of the trials so that a proper opinion of the potentialities of the weapon will be obtained. With modern complicated material the representatives of the military administrations must be technically qualified so that they will be competent to judge the practical use of the designs and the technical weaknesses, without being unduly influenced by the manufacturers' specialists.

In U.S.A. new weapons from private manufacturers are tested at military proving grounds, such as The Aberdeen Proving Ground, under the severest conditions possible. The trials are conducted by military specialists as it is considered that if private manufacturers dictate the testing program it is unlikely that it will be performed in a way which will show defects. Accurate testing instruments should, when necessary, be available so that the data will give a proper picture of the performances of the weapons and how they could be improved. Any numerical results should be subject to mathematical analysis. If insufficient data is obtained, the military staff will get a false opinion of the weapon from which important decisions might be taken.

ACTIVE-SERVICE FITNESS

War material is often subject to exceptional strains and must function under the very different states of weather. As an example, the Chrysler Corporation tested the electrical installation of a Sherman tank by trials during 1,500 hours on the beach of Florida. It is one thing to keep material in good condition in a workshop and quite another thing during a fight.

The weapons are in many cases not robust enough. War material should not be so complicated that normal damage cannot be repaired in battle by its own crew.

SECRECY

Secrecy is a necessary evil which to a large extent complicates the development of a new secret weapon. In military administrations this is not such a big problem as in a non-military industry. All drawings cannot be secret, and it requires good judgment to handle the security aspect to its best advantage. In addition to military security there are industrial manufacturing secrets which hinder cooperation (particularly in peace-time) between different manufacturers.

There are three types of secrecy:

I. The Ostrich.
II. The Red Box.
III. The Real Thing.

I. The ostrich buries his head in the sand of the desert when pursued by his enemy; and, because he can't see the enemy, concludes the enemy can't see him! Such is the secrecy of the secretive and detestable habit which hides from our own officers what is known to all the other Navies.

II. The secrecy of the red box is that of a distinguished Admiral who, with great pomp, had his red despatch-box, supposed to contain the most secret plans, carried before him, like the umbrella of an African king. But one day the box unfortunately capsized, burst open, and the contents that fell out were copies of *La Vie Parisienne*.

Such, it is feared, is the secrecy of those wonderful detailed plans for war which we hear of in secret drawers, to be brought out when "the time comes," and when no one has any time to study them—sup-

posing, that is, they ever existed; and, remember, it is detailed minute attention to minutiae and the consideration of trifles which spell success.

III. Lastly, there is the legitimate secrecy and secretiveness of hiding, even from your dearest friend, the moment and the nature of your rush at the enemy, and which particular one of all the variety of operations *you have previously practised with the Fleet* you will bring into play! But owing to this practice, all your Captains will instantly know your mind and intentions, for you will hoist the signal, or spark the wireless message, Plan A, or Plan B . . or Plan Z.

CONCLUDING REMARKS

There is a great risk that in military developments the organization becomes stiff and inflexible. Because of the public salary-system it is not possible to offer competitive salaries. This makes it difficult to enlist skilled technicians to solve the technical problems. Because of our limited means (especially as regards professionally skilled personnel, for the development of military projects) we must concentrate on just a few projects. We need people who can survey the weapon technical development and choose the right weapon projects, and we need the public research team with flexible organization and powerful resources to realize the project.

The world's largest naval vessel, the USS FORRESTAL, has an overall length of 1,036 feet, and with over 200,000 horsepower is capable of making 30 knots.

* * *

A modern submarine can fully submerge in less than 1 minute. Once submerged, it can travel faster than on the surface.

* * *

To rig for diving in a modern submarine, the crew must conduct 225 individual operational and equipment checks.

INFLUENCE OF THE ENGINEER ON SEA TRANSPORT AND TRADE

STERN-WHEELER TO NUCLEAR-POWERED SUBMARINE

ACKNOWLEDGEMENT

This is an abridged version of a presidential address given by Dr. S. F. Dorey, Chief Engineer Surveyor of Lloyd's Register of Shipping, on September 1, 1955, to Section G (Engineering) of the British Association. It was published in the September 9, 1955, issue of "Engineering."

THE SEAPORTS of the West country will long be famed for the part their seafarers and small but sturdy ships played in voyages of discovery. In the absence of foreign competition however British shipowners were complacent and the stagnant conditions of those days removed incentive both in shipbuilding and ship operation.

Throughout the Eighteenth Century naval architecture remained static and improvements were negligible in both the speed and size of sailing ships. At the end of the period, the Americans, having achieved political independence, were the first to break with tradition in the design and construction of merchant ships. They exploited the merits of fast, sleek sailing ships in place of lumbering heavily armed merchantmen, and this move soon proved a technical and commercial success.

In 1816, they were the first to establish regular sailings and a monthly service between New York and Liverpool commenced and by the 1840's the American merchant fleet had increased until it was the second largest in the world and comprised sailing ships which were second to no others. Moreover, their 50 years' sole experience in the construction and development of speedy clippers gave them an almost unsurpassable lead in sail.

INTRODUCTION OF THE STEAM ENGINE

Pioneer engineers had other ideas of the best means for propelling ships, and as early as 1801, Symington patented his method of constructing a steam engine which provided rotatory motion at a crankshaft through a piston rod and connecting rod, thereby eliminating the conventional lever or beam. A horizontal single-cylinder double-acting engine of this type was used to drive the crankshaft of the stern paddle-wheel steamer *Charlotte Dundas*. The successful trials of this first practical steamboat proved the potential merits of steam propulsion and inspired engineers on both sides of the Atlantic.

In 1807, Fulton employed British steam machinery to propel the paddle steamer *Clermont* on the Hudson River. This ship demonstrated the advantages of steam propulsion over sail for navigation on inland waterways, and early American developments concentrated on this aspect. In 1811, Bell introduced the famous paddle steamer *Comet* into service between the ports of the Firth of Clyde. Shipbuilders quickly appreciated the qualities of this ship and comparable vessels were soon building at all major British ports. With limited sheltered waters these steamers were used largely for coastal service and by 1826 appeared on the London to Portugal and Dub-

lin to Bordeaux routes. The working pressures of boilers were below 5 lb. per sq. in. and coal consumption of the steam machinery was little better than 10 lb. per i.h.p.-hour. In consequence the machinery and fuel occupied a large proportion of the available space in the ships and severely limited the freight-carrying capacity. Nevertheless, these steamers were a success and in the 1830's few steamship companies lacked financial support. Owners generally ploughed profits back into the companies and rendered a valuable service to commerce and steamship development by increasing their total tonnage with new construction. The burden of this practice was heavy but eventually proved sound policy, when, in 1837, the Government contracted private companies for the sea-carriage of mails.

Shipowners and engineers aimed at the conquest of the Atlantic by steam and to compete with the fast sailing-ships for the steadily growing passenger and freight traffic. By 1838, improvements in steam machinery had reduced coal consumptions to 5 lb. per i.h.p.hr. and the total fuel necessary for the crossing could now be carried. In that year the *Sirius* steamed continuously from Cork to New York in 19 days, but within a few hours of her arrival the Bristol-built *Great Western* arrived having steamed continuously from her home port on a maiden voyage of only 15 days. The latter ship undoubtedly stole the thunder and Sir John Rennie considered, at that time, that her performance was such that there seemed no bounds to the extension of steam navigation. That the first voyage of the *Great Western* was in no way abnormal is evident from her eight years' service prior to being broken up; a period in which she made 74 double crossings of the Atlantic with average outward and return times of 16½ and 13¼ days respectively.

IRON CONSTRUCTION AND SCREW PROPULSION

Constructional engineers and forge-masters had also been active since 1815 when a small sailing-ship with a wrought-iron hull plied the Mersey. This was followed three years later by an iron passenger-boat, *Vulcan,* which commenced operation on the Firth of Clyde, canal, while an iron steamer, *Aaron Manby,* navigated from Thames to Seine in 1822. Such small iron vessels were initially pre-fabricated in sections at the forges of the Midlands for transportation and assembly at the ports. As confidence grew, larger ships were built in the shipyards, and by 1850 Lloyd's Register Book contained the names of no less than 100 iron ships, more than half being steamers. Their size was generally below 550 tons, but the then colossal iron steamer *Great Britain,* of 3,618 tons, had already been in service for five years. Although a commercial failure, this venture was in many ways a technical success, establishing an inevitable trend to larger ships for ocean service. Moreover, her capacity to carry 1,000 tons of coal, 1,200 tons of cargo and 260 passengers represented a marked advance in the capabilities of the steam-ship.

The *Great Britain* was also the first large screw steamer to enter ocean service, and, although at an early stage of development and therefore less efficient than paddles, screw propulsion proved superior, as heavy seas could damage paddles and render them inoperative. The Admiralty was prejudiced against both iron construction and screw propulsion and on their instructions the early Cunarders which carried the Atlantic Mails were wooden-paddle steamers. It was not until the 1860's when a reduction in the hazards of fire, grounding and collision, had been attributed to iron construction, that relaxations were permitted. At the same time experiments instituted by the Admiralty had improved the performance of propellers to a stage that these, too, could be accepted.

Although developed to a reasonable state of reliability, single-expansion engines exhausting to surface condensers showed little improvement in fuel consumption. Steamers were, therefore, incapable of making the long voyages to Australia via the Cape, and completion of the journey was impracticable. Two alternatives were tried and both these were originated by the famous engineer Brunel and the equally eminent ship designer Scott Russell. The first was an iron ship, *Victoria,* of 3,000 tons, equipped with a small steam-engine driving a two-bladed propeller through gearing. The hull of the vessel was of greatly advanced design and a speed of ten knots could be obtained when the engines were operating, while six knots was maintained under sails. A voyage of 60 days from Gravesend to Adelaide won the Colonial Prize of £500 for the fastest journey. The second ship, the phenomenal *Great Eastern,* never confirmed the theoretical considerations on which her construction was founded. Brunel was of the opinion that this ship of 32,000 tons and carrying 10,000 tons of coal could steam the round trip to Australia without recoaling and, at the same time, carry sufficient cargo and passengers to provide a handsome return. The complete commercial failure of this ship is a well-known story but she must be credited with laying more than 100,000 miles of cable, which established communications across the Atlantic and offered shipowners a convenient means of arranging cargoes and controlling the voyages of their steamships.

COMPOUND ENGINES AND USE OF STEEL

It was abundantly clear that increased trade and traffic with the Far East and in the Pacific hinged on the improvement of economy of the main machinery of steamships. By 1854 advancement in the design and operation of iron boilers made working pressures of 25 lb. per square inch possible and also enabled Elder and Randolf to produce a practical compound engine in which the steam underwent a second stage of expansion. The first engine installed in the *Brandon* showed a fuel consumption of 3¼ lb. per i.h.p.-hr., but early engines of this type suffered from want of reliability. Two years later the Pacific Steam Navigation Company put two paddle steamers, *Inca* and *Val-*

pariso, into service and each was fitted with compound engines. Three other ships of this company were then re-engined with this type and one of these ships, the *Bogota,* displayed a 50 per cent fuel saving after re-entry into service. Up to 1866 Elder and Randolf alone had built 48 sets of compound engines which were mainly operating in the Pacific. At the same time the P. and O. Company had ten ships propelled with compound engines in general operation and the Blue Funnel Line had three. The latter company were able to run 8,500 miles from England to Mauritius without recoaling.

A century ago Bessemer patented the converter process for the manufacture of steel and the products of early practice were used almost exclusively for hull construction, the quality not being found consistently reliable for boiler-making. Nevertheless, valuable experience was gained in the manipulation of steels in the ship-yard and hastened the extensive use of the high quality and cheaper materials made available in quantity by the later Siemens-Martin open-hearth process. Steels led to a minor revolution in shipbuilding and boiler and machinery construction. The superiority of steel over wrought iron permitted a 25 per cent. reduction in the scantlings of principal component parts representing a saving in weight of over 100 tons per 1,000 gross tons of ships, as well as reducing power plant weights. These savings were important at a time when steamers had to carry large quantities of fuel. An even greater effect of steel construction was evident in boiler practice, however, for within a few years working pressures increased threefold and brought about improved economy and reduction of unit size.

During the 1880's triple expansion superseded those of compound type on the Atlantic. At the same time multi-screw propulsion was adopted to meet the demands of steam-ship companies for greatly increased power of single ships. Moreover, competition was keen for the trade and passenger traffic, and speed and size of ships were matters of international rivalry. It was these events which led to the realization of Brunel's conception when he planned the *Great Eastern,* but 40 years of engineering progress had to pass before similar ventures could be undertaken without the risk of complete commercial failure.

STEAM TURBINES

Of the liners fitted with triple-expansion engines the twin-screw *Campania* of 12,950 tons and 601 ft. in length, may be quoted. Built in 1893 the engines developed a total of 31,000 i.h.p. and propelled the ship at 22 knots. About the same time the quadruple-expansion engine was evolved and offered further economy in operation. The largest steam reciprocating engines built were of this type and engined the liner *Kaiser Wilhelm II.* 43,000 i.h.p. was obtained with steam raised at 225 lb. per sq. in. pressure in 14 double-ended and seven single-ended cylindrical boilers. Power/weight ratios of large reciprocating machinery installations ranged from 6 to 7 i.h.p. per ton and the total weight of the quadruple machinery of the *Deutschland* weighed no less than 5,670 tons for 38,900 i.h.p. In addition, unpleasant hull vibrations were excited by the heavy reciprocating masses and were detrimental to the comfort of the passengers. For these reasons steam reciprocating machinery was not entirely suitable for high-powered liners and the limit of total power of the ship had been attained so far as these prime movers were concerned.

It was not suprising, therefore, that Parson's *Turbinia* was acclaimed as an outstanding triumph, for it offered the solution to these problems. Nine years later, in 1905, the 30,000-ton liner *Carmania* was engined with steam turbines of 21,000 s.h.p. and after a further two years the quadruple-screw liner *Mauretania* was completed with single reduction geared turbines of 70,000 total s.h.p. A speed of 24½ knots won this liner the Atlantic record which she retained for a 22-year period signifying that she represented the end of the first era of national and international rivalry for the largest and fastest ship afloat.

During this era shipowners had also been able to equip their fleets with ships of increasing size, for expanding trade had always proved their speculation sound. The British Merchant Fleet had increased by no less than 5,000 ships in half a century and in the latter half of this period other nations had recognized the achievements of British engineering and built up fleets of merchant steamships for their own purposes. In consequence, there was now a tendency to adopt economical sizes of each type of merchant ship and many wondered whether a ship like the *Mauretania* could be a paying proposition. Further, trans-ocean cables which had been laid by steamships and the recently introduced wireless telegraphy enabled ships to operate more economically by reducing the delays at ports. Owners were, therefore, able to prearrange cargoes and ascertain the exact whereabouts or progress of the ships in their fleet. On the other hand, the rapid growth in world merchant ship tonnage and the availability of telegraphic communication stimulated competition and full cargoes were not readily obtainable.

For the engineer the conquest of the trade routes by steam navigation was complete and the steam reciprocating and turbine machinery had attained a high degree of reliability with reasonable economy. His role had therefore changed from a pioneer to a consolidator; adapting, modifying and developing the various types of machinery at his disposal to meet the many requirements of shipowners and operators.

USE OF OIL FUEL

By the end of the Nineteenth Century the supplies of heavy oil fuels were sufficient to warrant consideration as an alternative to coal for firing the boilers of steamships. The advantages of liquid fuels in respect of transportation, handling and storage were obvious, but it was not until 1894 that an oil-burning steamer, the *Baku Standard,* entered sea service. In the first half of this century coal burning has been almost en-

tirely replaced by oil burning for sea-going steamers and so far as new construction is concerned, the change-over is virtually complete.

The next landmark in marine engineering was the oil engine which was introduced as a main prime mover for ocean-going merchant ships in 1910, when the 1,179-ton tanker *Vulcanus* was completed and engined with a Werkespoor six-cylinder 4 S.C.S.A. Diesel engine of 500 b.h.p. rating at 200 r.p.m. It may be of interest that this engine was still operating satisfactorily when the ship was sold for scrap in Japan, 20 years later. A greater advance was represented by the Burmeister and Wain Diesels which engined the twin-screw motorship *Selandia* of 5,000 tons. Completed in 1912 each eight-cylinder 4 S.C.S.A. engine developed 1,050 b.h.p. at 140 r.p.m. and showed that the problems of high-powered oil engines were being effectively overcome. This installation was so revolutionary as to attract the attention of the world. Sir Winston Churchill, then First Lord of the Admiralty, visited the ship and examined the machinery layout. On this occasion he said that . . . "it was a pleasant duty for him to congratulate Denmark, the ancient seafaring nation which had shown us the way and taken the lead in a venture that will form an epoch in the development of shipping." As on many other occasions, history has confirmed the validity of his shrewd judgment. The *Selandia* was in operation until 1942 when she was wrecked. During the life of this ship the oil engine had become the predominant prime mover for new merchant ships constructed in the world, and by 1939 engined more than one-quarter of the total number of ships afloat.

Following the 1914-18 war, shipowners were faced with the problem of rebuilding their total tonnages to make good the losses during the hostilities. They had struggled to achieve this aim without subsidy when trade eased and competition became keen to secure freights. Reductions in fuel costs were of vital importance and it was this aspect which received the attention of engineers. The triple-expansion steam engine then operating with saturated steam supplied by Scotch boilers of 200 lb. per sq. in. working pressure, offered fuel consumptions of 1.6 lb. of coal or 1.1 lb. boiler oil per i.h.p.-hour. Steam-engine makers soon developed improved designs incorporating such features as poppet valve gear and uniflow exhaust of cylinders, and capable of operating with superheated steam at total temperatures approaching 700 deg. F.

The inability of the reciprocating engine to utilize all the possible expansion of the steam due to limits imposed on the size of the L.P. cylinders was overcome by the fitting of exhaust steam turbines. This was no new feature, for Parsons used a reaction turbine supplied with exhaust steam from two reciprocating engines and driving an independent shaft directly, in the triple-screw steamship *Otaki* completed in 1908. Before this arrangement was superseded by the geared-turbine for passenger ships, a number of other installations were completed, including those of the *Olympic* and *Titanic*.

The arrangement first fitted in a single-screw ship in 1926 was the Bauer-Wach system, in which the drive from the turbine was transmitted through double-reduction gearing and a fluid-coupling back to the reciprocating engine main shaft. Other manufacturers preferred electrical to mechanical transmission and in these cases the exhaust steam turbo-generator with either a.c. or d.c. output supplied an electric motor mounted at a convenient position on the main propulsion shaft.

Reheating of the steam before admission to the medium-pressure cylinder of the engine also offered appreciable improvement in performance. The direct method of raising the conditions of the high-pressure exhaust used a heat exchanger supplied with superheated steam direct from the main boiler unit. As an alternative, an exhaust turbine was used to drive either a d.c. generator which supplied electrical heating elements or a steam compressor.

Each of the improved steam reciprocating installations had its own particular merits and champions. Fuel consumption of just under 1 lb. coal or 0.8 lb. oil per i.h.p.-hour could now be offered and these represented appreciable savings in overall fuel costs. Nevertheless, progress in the oil-engine field had been so marked as to offer a serious rival to the steam reciprocator.

THE DOXFORD ENGINE

In 1914 Doxford and Sons, Limited, of Sunderland, ran endurance trials on a single-cylinder, two-stroke cycle, heavy-oil engine, which embodied the opposed-piston principle and developed 450 b.h.p. at 125 r.p.m. This represented a major advance in the power output of a single cylinder. During the 1914-18 war the performance of both four-stroke and two-stroke oil engines progressed rapidly and this was assisted by the adoption of solid injection of the fuel: an important departure from the Diesel principle.

By 1921, two-stroke types of four cylinders were providing 3,000 b.h.p. on a single-screw, but four-stroke types nevertheless predominated in marine practice. Four years later, double-acting engines of the latter type displayed single cylinder outputs of 1,100 b.h.p. The twin-screw motorship *Gripsholm*, for example, was directly propelled by two six-cylinder engines of this type, 33 in. in bore and 59.1 in. stroke, with a total output of 13,500 b.h.p. at 125 r.p.m. Doxford's soon challenged this achievement by building engines of the two-stroke type described and the 5,000 total b.h.p. represented 1,250 b.h.p. per cylinder.

At this time many of the service problems experienced with the two-stroke oil engines had been surmounted and a number of engine builders who had previously favored four-stroke types now regarded the former as a better proposition. In consequence the passenger liners *Britannic* and *Georgic*, completed in 1930 and each fitted with two ten-cylinder engines of

20,000 combined b.h.p., represented a peak in the progress of the four-stroke type. Thereafter preference for the various two-stroke engines prevailed until the present day, when they form no less than 80 per cent of the main oil-engines fitted in ships. Further, the fitting of Buchi superchargers to engines of the four-stroke type, although giving improved performance, had little effect on the predominance of the two-stroke engines.

By 1934 two-stroke engines were supplying up to 7,000 b.h.p. on a single screw and the replacement of cast-iron bed plates, entablatures and columns by welded fabrications in mild steel did much to reduce the weight and size of the engines. In addition, renewed attention was given to the use of exhaust gases to raise steam in waste heat boilers which augmented the supply from the donkey boilers and reduced overall fuel consumption of the auxiliary machinery.

After that time the power of heavy oil engines continued to increase steadily. In post-war years, however, the successful adaptation of a moderate degree of supercharging in two-stroke engines had provided 30 to 35 per cent increase in power with m.i.p.'s of up to 130 lb. per sq. in. Engines are already under construction with single cylinder outputs of 1,650 b.h.p. and further increases to 2,200 b.h.p. are contemplated. Large slow-running engines therefore develop 10,000 to 17,000 b.h.p. and offer a serious challenge to the geared steam turbine for the propulsion of single-screw tankers and cargo ships. Without increase in the weight of the installation, two medium-speed oil engines coupled through 2 : 1 reduction gearing to a single shaft have also been employed to develop these powers. The gearing is protected from engine-excited torque fluctuations by either fluid or, more recently, electromagnetic couplings installed between engines and pinions. Moreover, such arrangements show considerable advantages during maneuvering. Although two-stroke engines are usually used for a propulsion unit of this type, highly supercharged four-stroke engines are also available when slightly lower powers are required.

Modern oil engines have excellent fuel consumptions of about 0.32 lb. oil per b.h.p.-hr. which correspond with overall efficiencies of 40 per cent. The most important feature of slow and medium-speed engines has been their recent conversion for burning boiler or residual grades of oil, however. The use of these fuels can provide a saving in fuel costs of up to 30 per cent. This achievement has given the oil engine a substantial lead over rival prime movers but the approach towards the theoretical efficiency leaves little scope for greater economy.

CYLINDRICAL OR WATER-TUBE BOILER

Before the 1914-18 war, water-tube boilers had superseded those of cylindrical types in warships and had proved superior in performance and operation. The working pressure of boilers in merchant ships advanced slowly during the first quarter of this century and the maximum employed was little in excess of 250 lb. per sq. in. Over this period the cylindrical boiler predominated throughout the whole power range of steam machinery. A considerable number of water-tube boilers were installed in merchant ships during the Great War, however, but their satisfactory service did little to dispel the prejudice against them except in America, where war-time construction comprised the major part of the merchant fleet. The development of economical steam-turbine machinery installation during the 1920's demanded H.P.-inlet conditions which could no longer be met by cylindrical boilers and the water-tube type now controlled the field of high-pressure and high-temperature steam production.

The benefits of advanced steam plants were soon evident by the appreciable reductions in specific fuel consumptions. The S.S. *Duchess of Bedford,* completed in 1928, was fitted with Yarrow boilers with a working pressure of 340 lb. per sq. in. at 670 deg. F. total temperature. The fuel consumption of the main machinery was recorded as 0.57 lb. per s.h.p.-hr. When compared with a Scotch boiler installation of eight years earlier a fuel savings of at least 15 per cent was evident. Three years later the *Empress of Britain* entered service and her full power of 60,000 s.h.p. was developed by turbines supplied with steam at 425 lb. per sq. in. and 725 deg. F. On trials the same fuel consumption was recorded, but in this case it represented the all-purpose requirements. An appreciable advance in the use of higher steam conditions occurred in 1936 when construction commenced on the turbo-electric tanker *J. W. Van Dyke.* The two Babcock and Wilcox boilers of this ship were designed for a maximum working pressure of 675 lb. per sq. in., the superheater outlet steam being at 625 lb. per sq. in. and 835 deg. F. The fuel consumption of the main machinery was approximately 0.51 lb. per s.h.p.-hr. In the sister tanker *Robert H. Colley,* laid down in 1938, the steam temperature was raised to 910 deg. F., which was the most advanced condition used in merchant ships in the pre-war and early war years.

Some remarkable high-pressure installations were also completed, notably the 3,200 lb. per sq. in of the Benson boilers in the *Uckermark,* 1990 lb. per sq. in. by Loeffler type in the *Conti Rosso* and the *Potsdam* with 2,650 lb. per sq. in. working pressure. Such high pressures were rarer, however, and the main object has since been for pressures below 1,000 lb. per sq. in. with high degrees of superheat.

Water-tube boiler makers were active in their design advancement and by 1938 boiler efficiencies of 87 per cent were possible. This was partly responsible for the low overall fuel consumptions of propulsion machinery. Of equal importance were the increases made in total heating surface and the rates of evaporation produced by single boilers for this permitted boiler plant of reduced size and weight. In addition, high quality fusion-welded joints replaced those of riveted type in the fabrication of boiler drums and by this means weight saving alone exceeded 1¼ tons per drum.

In America the Scotch boiler had practically died out by 1939, for a year later special arrangements had to be made to supply boilers of this type for 60 cargo ships ordered by Britain. In Britain, however, the cylindrical boiler has retained some of its popularity for both main and auxiliary steam generation, due to its rugged characteristics and it is usual practice to use water-tube boilers where steam pressures exceed 300 lb. per sq. in. Steam-turbine installations at present engine ships of 50,000 s.h.p. per screw or 200,000 total s.h.p. and as greater powers will not be required for some years, it is natural that research should be concerned with reducing fuel consumptions well below 0.5 lb. per s.h.p.-hr. and developing more compact plants. Economical units incorporating one or more reheat points are at present under consideration and it seems that gas-fired reheaters will supersede those of steam type. Increased steam conditions at the H.P.-turbine inlet still present a major source for improved economy. The tanker *Atlantic Seaman*, which has been in service for five years, has a turbine plant working with inlet steam at 600 lb. per sq. in. pressure and 1,020 deg. F. This machinery remains in advance of other merchant-ship installations and fabrication, design and service problems of high temperature materials are largely responsible for this position.

Of the ships at present under construction all in excess of 20,000 tons will employ geared steam turbines for main propulsion. Within the size range 100 to 20,000 tons, 70 per cent will be propelled by oil engines, while the remainder, with isolated exceptions, will have steam reciprocating or turbine main machinery. Turbo- or Diesel-electric transmission have not proved popular although restricted gear-cutting machine capacity increased the number of installations of these types during the last war. In some instances, however, turbo-electric main machinery has been preferred for large oil tankers in order that the main generator could be used to supply the cargo pumps when in port.

Both tankers and ore carriers have increased in size to meet the needs of supplying the expanding oil, chemical and metallurgical industries. Vessels of these types at present rival large passenger ships in size, but retain single-screw propulsion. To meet these conditions steam turbine manufacturers in particular have developed compact power plants developing up to 20,000 s.h.p. Further progress is continuing in this direction and double-reduction gearing in particular is the subject of extensive researches. The problems of successful transmission of gear-tooth loads of two and three times recognized pre-war levels have not yet been satisfactorily solved and surface hardened and ground gears are at present under consideration.

GAS TURBINES AND NUCLEAR REACTORS AS POWER SOURCES

In recent years other forms of prime mover have been considered for merchant ship propulsion, but so far these have not proved sufficiently attractive for general service.

The marine gas turbines at present under development for marine propulsion purposes are of open-cycle type. In general, the H.P. turbine drives an axial compressor as an independent unit while the L.P. provides the useful output and exhausts through a heat exchanger which preheats the inlet charge to the combustion chamber. The designs vary considerably, but can be considered in two main categories. The first covers those of lightweight construction, under 7 lb. per h.p. and developing up to 6,000 s.h.p. The H.P.-inlet temperatures of about 820 deg. C. limit the life of the hot parts to little more than 1,000 hours. Units of this type power light naval craft only, for a satisfactory life, in excess of 20,000 hours is required for the main engines of merchant ships. This is at present obtained by limiting the top temperature to below 700 deg. C. in medium-weight plants of 25 to 30 lb. per s.h.p. Both classes of gas turbine have overall efficiencies of about 20 per cent, but when the long service reliability of the latter has been established, advances in top temperatures and design should provide fuel consumptions below 0.5 lb. per s.h.p.-hour. Since these engines cannot be run astern, either electric transmission, reversible-pitch propellers or reduction gearing with reverse trains must be used. Of these, the last quoted is receiving the greatest attention and is likely to predominate in future installations.

In France remarkable progress has been made recently in a power plant comprising a free piston gas generator and geared gas turbine. Turbine inlet conditions of four atmospheres pressure and less than 500 deg. C. are used as the peak temperature of the thermodynamic cycle occurs in the cylinder of the free piston gas generator. Overall thermal efficiencies therefore approach those of existing oil engines and are represented by a fuel consumption of 0.39 lb. Diesel oil per s.h.p.-hour. The problem of maneuvering does not apply in this instance as astern wheels are incorporated in the turbine shaft.

The size of the gas generator has been standardized so that equal reliability may be obtained with all units. High-power plants will, therefore, comprise multiple units supplying one or more geared turbines. The first main marine installation of this type was installed in the 800-tons d.w. *Cantenac*, completed in 1954, and other ships at present under construction will be similarly fitted.

The construction of two submarines for the U.S. Navy in which the heat developed in a nuclear reactor is used to raise steam for supplying both main and auxiliary turbine machinery, has resulted in wide speculation of the possible adoption of similar power plants for merchantship applications. Indeed such an impressive statement that the fissioning of 1 lb. of uranium produces heat equivalent to 2,300 tons of coal or 300,000 gallons of oil, raises visions of revolutionary changes in the design of merchant ships and their machinery. As these changes would solve

many existing problems, it seems that thermal reactors must eventually provide the energy for steamship propulsion. When this event will be possible depends on the rate of progress made in reducing to more attractive levels the weight, size and cost of reactors and screening and the satisfactory solution of control and maintenance problems. It appears that the power/weight ratios of these units will be better suited to the higher-powered plants of large cargo and passenger liners than to the many low-powered installations in smaller ships. Undoubtedly, the latter will continue to be engined with conventional prime movers.

In the submarine U.S.S. *Nautilus*, purified water under high pressure forms the primary coolant which extracts the heat from the thermal reactor. The steam then raised in heat exchangers is relatively low pressure and temperature, probably not more than 180 lb. per sq. in. and 440 deg. F.; consequently, geared steam-turbines of moderate thermal efficiency are used and high temperature is confined to the primary coolant section. In effect, the controlling factor is the rate at which heat can be extracted from the small volume of the thermal reactor and providing this is adequate to meet the demands, thermal efficiency is of only secondary importance. It is related to the size of plant, however, and for this reason fast reactors and liquid metal primary coolants may be superior for steamships.

An examination of the history of one particular field of engineering has indicated that the remarkable increases which have occurred in the prosperity of nations, during the last century and a half, can largely be attributed to the achievements of the engineer. It is also true that the countries which have encouraged engineers and industry enjoy the highest standard of living. Today we aim to improve our living standard still further and, at the same time, assist other countries to do likewise. That the engineer is continuing to play his part is evidenced by the high rate of technical progress maintained during postwar years.

The first submarine accepted by the Navy, the USS HOLLAND, was built in 1899 at a cost of $236,600. The Navy bought it for $150,000. Present day submarines cost upward of $10,000,000.

NATIONAL GAS TURBINE ESTABLISHMENT

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(1) TEST FACILITIES

When the National Gas Turbine Establishment was set up in 1946 it inherited a small amount of test facilities from its forebears, the engine department of the Royal Aircraft Establishment, and Power Jets (Research and Development), Limited, the main items of which were a 4,000 h.p. motor-driven air-compressor set at Pyestock for combustion and gas-turbine work, and a 6,000 h.p. steam turbine at Whetstone to provide shaft power for compressor testing. Both these pieces of plant have been, and still are, of great value. Two major modifications of the 6,000 h.p. compressor rig at Whetsone have been carried out. The plant for testing turbine rotors has been removed from the atmospheric compartment, which is now equipped for testing compressors. Thus the steam turbine is now employed to drive compressors at either end. An activated alumina bed has also been provided to remove moisture from the air being passed to the altitude chamber. Since 1946 additional plant has been steadily added, and almost without exception this development has taken place at Pyestock, with the object of concentrating the main resources of the Establishment on this site.

The original 4,000 h.p. air-compressor set in the compressor house was duplicated, and an additional compressor set operating at a higher pressure was added. A range of high-speed gearboxes was provided which enabled experimental compressors to be tested by taking the drive from the original motor. The air supplies from the compressor house were augmented by a battery of five jet engines from which air is bled. All the air is piped into test cubicles adjacent to the compressor house. Air is also supplied to the nearby fuel and power laboratory in which work on coal burning as applied to gas turbines is carried out. Tests requiring a suction supply to simulate reduced atmospheric pressures at high altitudes take place in cubicles fitted with ejectors. Here the air from the compressor house is passed through liquid-fuel-fired preheaters with water added to produce a fluid of mixed products of combustion and steam which work the ejectors.

With the exception of the fuel and power laboratory, all these additional facilities were installed in existing buildings, or extensions to them, on what is now the old part of the Pyestock site. The need for still larger test facilities to match the rapid development of the gas turbine meant that new buildings and more test plants had to be provided, and so a larger group of buildings was erected on an adjoining site at Pyestock.

The largest of the new buildings, the plant house, contains two 9,000-h.p. motor-driven compressors which, with an air-bleed gas-turbine set, provide compressed air for tests in a number of large combustion and aero-dynamic test cubicles. The two motor-driven sets can also operate as exhausters for giving sub-atmospheric conditions in the test cubicles. Nearby is a compressor and turbine test house, known as the Battle test house, because its boilers were taken from an uncompleted "Battle" class destroyer. Steam from the boilers drives a 15,000 h.p. high-speed steam turbine, which is similar to the smaller plant at Whetstone, and supplies the shaft power needed for compressor testing. Air mains interconnect the compressor and gas-turbine test-beds

in this building with the machines in the plant house. Power to run the electrically-driven plant is supplied from a large sub-station which is connected at 33,000 volts to the Southern Electricity Board's system. A gas turbo-alternator set is under construction in the power station (Fig. 2) which will feed into the Establishment's electrical system, whilst waste heat from the machine will be used to heat most of the buildings.

Also under construction is a facility for testing ram jets and aircraft engines at high forward speed. This plant will be supplied with compressed air from the plant house and the Battle test house. The air may be used to give a pressure supply in either of two large cylindrical test cells, or for working ejectors to give suction conditions to the engine on test. It is intended that this plant will be used extensively for work related to supersonic flight.

A 600 h.p. motor-driven high-speed rig has been put into use recently for overspeeding and bursting turbine and compressor rotors, in the dynamics laboratory.

Bulk liquid-fuel supplies brought in by road are delivered to a tank farm from which the various grades are fed to small pump houses serving each of the main test buildings.

In addition to the wide range of facilities available for research work and component testing, there are a number of conventional test beds on which complete engines can be tested under sea-level conditions. Noteworthy among these is the Admiralty test house (Fig. 1) in which gas turbines up to 10,000 s.h.p. for marine propulsion, together with gas turbo-alternator sets, can be endurance-tested under conditions approaching those met with in service.

Cooling water for test plant is drawn from the nearby Basingstoke Canal and from the Mid-Wessex Water Company's mains. Water is stored in two large circular reinforced-concrete reservoirs and, wherever possible, is recirculated through induced-draft cooling towers.

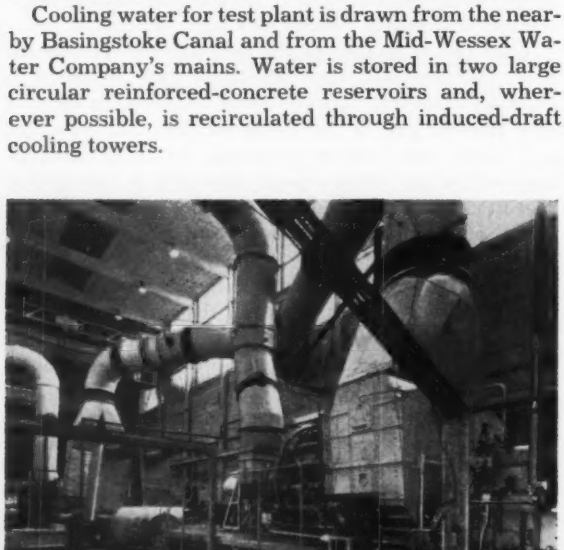

Fig. 1. The Admiralty test house, used for proving main-propulsion and auxiliary gas turbines up to 10,000 s.h.p. for naval use.

COMPRESSOR HOUSE

The compressors installed in the old compressor house fall into three groups, of different delivery pressure, namely: 30, 45 and 135 lb. per square inch gauge. Air in the first group is supplied by a 600 h.p. motor-driven Howden-Lysholm compressor, which works on the rotary screw principle. Running at a constant speed of 3,000 r.p.m., this machine is capable of delivering 6.6 lb. of air per second at a constant temperature of 100 deg. C.

Air at a pressure of 45 lb. per square inch can be supplied by two compressors. One of these, a 4,000 h.p. British Thomson-Houston centrifugal type compressor, with four stages, is driven through a Ward Leonard variable-speed set, which makes possible a compressor speed range of from 3,500 to 7,000 r.p.m A motor-generator set supplied at 6,600 volts alternating current generates a direct-current output for the driving motors. The maximum output of this compressor at the design pressure ratio is 26 lb. of air per second. The machine is uncooled, but air may be passed through an aftercooler to reduce its temperature from 190 deg. to 30 deg. C. if desired.

The second machine in this group is a Demag four-stage uncooled centrifugal compressor, driven through gears by a 4,000 h.p. slip-ring induction motor, with a speed range of from 3,750 to 5,100 r.p.m., which is obtained by the use of a liquid resistance. The designed output of the compressor is 29 lb. of air per second. The delivered air may be cooled from 190 deg. to 30 deg. C. by an aftercooler.

Air at the maximum pressure of 135 lb. per square inch is supplied by a Demag nine-stage centrifugal compressor which may be run at any speed between 4,900 and 7,000 r.p.m. This machine is fitted with an intercooler and aftercooler, and at the designed pressure ratio delivers 10 lb. of air per second at a constant temperature of 25 deg. C.

The two Demag compressors are driven from the same double-ended motor, which is coupled, by mean of clutches, to whichever compressor is required. Hence it is possible to run only one of these compressors at any one time.

In addition, air at a pressure of 45 lb. per square inch gauge can be supplied by five modified Rolls-Royce Nene air-bleed gas-turbine engines, situated outside the building. The nozzle guide vanes on these aircraft jet engines have been modified so that 12 lb. of air per second may be bled off each machine. This air is fed into the compressor house 45 lb. per square inch air main, to boost the air flow at this pressure up to a maximum of approximately 115 lb. per second of air.

Test rigs may also be exhausted by ejectors, driven by air supplied by the compressor plant. Four of these ejectors are installed in the cubicles, the largest being capable of exhausting 12 lb. of air per second. Two 90 h.p. Holland rotary exhausters are provided for

auxiliary exhausting duties. These machines, running at a constant speed of 585 r.p.m., are each capable of exhausting 2.5 lb. per second of air. To protect the machines, the hot exhaust gases are cooled to 40 deg. C. before passing through the exhauster.

Water for plant and test cooling is pumped at the rate of 186,000 gallons per hour and is recirculated after being cooled in an induced-draft cooling tower. In addition, 37,200 gallons of water per hour may be injected into hot exhaust streams, to reduce the temperature of the gases and to inhibit explosion.

Installed in the compressor house is a 4,000 h.p. rig, used for driving experimental compressors under test. The compressor to be tested is driven by the British Thomson-Houston compressor motor through primary and secondary step-up double-helical gearing. The secondary gearbox may be easily removed, and replaced by a gearbox of different ratio, so that, by fitting the required gearbox and adjusting the motor speed, the compressor may be driven at any speed up to 14,010 r.p.m.

FUEL AND POWER LABORATORY

The fuel and power laboratory, built to facilitate research on coal-burning combustion chambers and associated plant, is divided into two main sections: the coal-preparation room and the laboratory in which combustion testing is carried out.

The British Rema plant installed in the preparation room delivers either granulated or powdered coal at the rate of 1 ton per hour. The coal is fed from one of four bunkers into a feed hopper, from where it is passed through a hammer mill to be crushed to a fineness of less than ⅛ in. The granulated coal is then mechanically cleared of stones, and then fed through a dryer, and dryer cyclone, where hot air is employed to reduce the moisure content to less than 1 per cent. The coal is then fed into a 5 ton reserve capacity bin, ready for use in the laboratory.

If, however, powdered coal is required, the granulated coal leaving the dryer cyclone is passed through a ring-roll mill and classifier where it is finely pulverized before entering the reserve capacity bin.

The granulated or powdered coal leaving this bin is fed, through an Avery "weigh-feeder," to a coal pump which forces the fuel into the combustion chamber under test. The coal pump consists essentially of a short cylindrical element, with axis vertical, which is motor driven through reduction gearing at a speed of 13 r.p.m. This element, which bears a resemblance to the revolving magazine of a repeating revolver, has a number of cylindrical ports drilled parallel to its axis. Coal is gravity-fed into these ports, and, as the cylindrical element revolves, each port in turn comes into line with a port in the pump casing which admits air at a pressure of 100 lb. per square inch to blow the charge of coal out of the element port, and into the combustion chamber. The capacity of this pump is 2 tons per hour, which is double the capacity of the coal preparation plant. The reserve-capacity bin, however, may be filled before testing is commenced, and thus fuel may be burned in the combustion chamber at the rate of 2 tons per hour for a period of approximately 5 hours.

PLANT HOUSE

The plant house, brought into operation last year, is similar in principle to the compressor house, but the improved facilities allow combustion and aerodynamic research to be carried out on a much larger scale.

The compressors, installed in a central plant hall, discharge into 24 in. diameter mains, which distribute the compressed air as required to test cubicles along two sides of the building.

The main compressor plant consists of two similar Metropolitan-Vickers motor-driven axial-flow compressor sets which may work independently or in parallel. Each 17-stage compressor is driven through gears by an 8,850 h.p. three-phase 11kv auto-transformer-started salient-pole synchronous motor at a constant speed of 7,150 r.p.m. The combined weight of compressor, gearbox and motor is approximately 27.5 tons.

Each machine is capable of delivering 60 lb. of air per sec. at the maximum delivery pressure of 74.8 lb. per sq. in gauge. An aftercooler is provided to reduce the air temperature from 250 deg. C. down to a minimum of 50 deg. C. If, however, hot compressed air is required at the cubicles, the air is passed through the main pipework at a temperature of 250 deg. C. and may then be further heated to 400 deg. C. immediately before entering the test cubicle. This heating is carried out by means of an electric heater of 1,500 kw capacity, power for which is supplied by a Metropolitan-Vickers alternator set, comprising two 430-volt three-phase 1,500 kw alternators, driven by an 11 kw synchronous motor through a double shaft extension.

The two motor-driven compressors may also be used to exhaust air, or the exhaust gases, from test equipment in the cubicles. When used as an exhauster, each machine will exhaust 8.62 lb. of air, per sec. the inlet pressure being 2.45 lb. per sq. in. absolute, and the outlet pressure atmospheric. To protect the machine, hot exhaust gases must be cooled before entering the exhauster, and this cooling is carried out in two stages. The gases are first passed through a gas cooler which is designed to cool the full duty of one exhauster from 1,000 deg. to 250 deg. C. at any pressure below atmospheric. At this reduced temperature, the gases are passed through 48 in. diameter pipework to the exhauster precooler, where they are further cooled to 50 deg. C. before entering the machine. The gases are then discharged through a silencing unit to atmosphere.

In addition to the two main exhauster-compressors, a Parsons air-bleed gas turbine has been installed to supply smaller quantitise of compressed air for special duties. This turbine develops a s.h.p. of 9,470 when running at its maximum speed of 4,600

r.p.m. Of the 87.4 lb. of air per sec. passing through the compressor, 25 lb. of air per sec. are bled off into the 24 in. diameter pressure main. This air is delivered at a pressure of 44.8 lb. per sq. in. and a temperature of 191 deg. C., the latter being reduced when necessary by means of an aftercooler.

The large quantities of cooling water required are pumped through a 30 in. diameter water main, and returned to cooling towers working on the induced-draft system. One tower, operating with the gas coolers, has a flow of 240,000 gallons per hour with a temperature range of 86 deg. to 38 deg. C. The second tower is capable of reducing the temperature of 273,000 gallons per hour of plant cooling water from 42 deg. to 30 deg. C.

The test cubicles contain a total of 22 testbeds, which consist of reinforced concrete with broad flange joists in the top surface capable of absorbing a 90-ton load at 3 ft. 6 in. center height. Take-off points on the air mains are provided opposite each test-bed, and from these points branch pipework is erected as required so that air may be supplied to, or gases exhausted from, the test equipment in the cubicles.

BATTLE TEST HOUSE

Plant in the Battle test-house like that of the 6,000 h.p. rig at Whetstone, is installed for the purpose of driving compressors under test, but here the available power is greater.

Two Yarrow-type boilers, similar to those fitted in H.M. destroyers of the "Battle" class, are each capable of an evaporation rate of 250,000 lb. per hour, at a pressure of 400 lb. per sq. in. and a temperature of 650 deg. F. This steam is used to drive a condensing steam turbine designed and supplied by Brush Electrical Engineering Company, to develop 15,000 h.p. when running at its maximum speed of 12,500 r.p.m. As at Whetstone, the combination of power and speed makes it necessary to work the turbine on a low vacuum, and employ reduced blade lengths which do not involve unduly high stresses. The turbine, of axial-flow type, with blading designed on the vortex-flow principle, drives at either end so that compressors of either rotation may be tested.

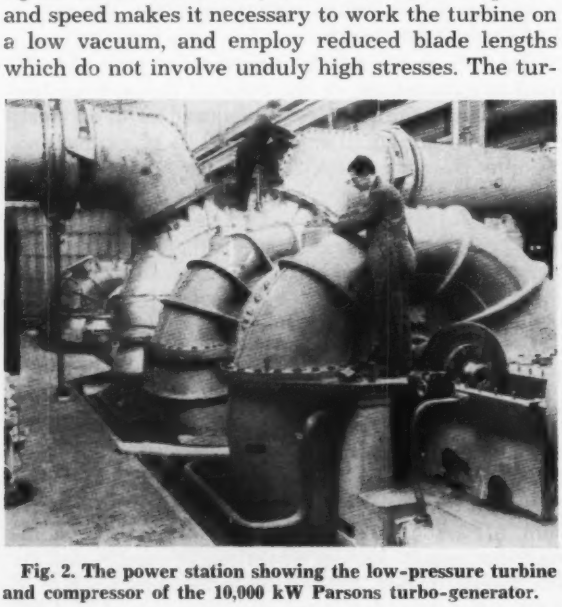

Fig. 2. The power station showing the low-pressure turbine and compressor of the 10,000 kW Parsons turbo-generator.

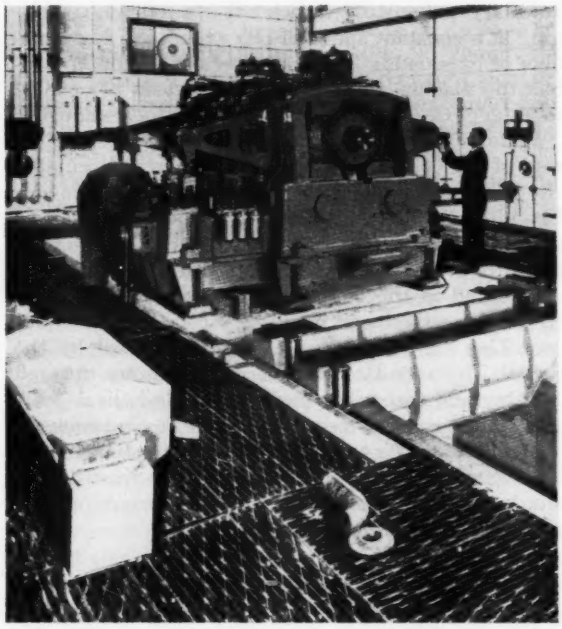

Fig. 3. The 25,000 h.p. Heenan and Froude dynamometer installed in the Battle test house will be used for turbine tests.

During test running, remote control is maintained from a control room outside the steam turbine compartment. In an emergency, the turbine may be hand tripped from any one of five positions, while automatic tripping follows the failure of turbine or compressor lubricating oil, failure of condenser vacuum or an undue rise in condenser water level, undue vibration of the compressor under test, or loss of compressor blade tip clearance. In the control room itself are the measuring instruments relating to the aerodynamic performance of the compressor; the purely mechanical aspects—bearing temperature, vibration amplitudes, etc.—are measured in a room below the control room.

The 25,000 b.h.p. Heenan and Froude dynamometer (Fig. 3) in a separate compartment will be used to brake gas turbines under test. During such testing, a large pressure drop through the turbine may be maintained by means of the exhauster/compressors in the plant house, which are connected to the Battle test house system by 48 in. diameter pipework. Water for condenser and plant cooling is circulated in a closed system, and cooled by means of concrete cooling towers working on the induced draft system.

GAS-TURBINE POWER STATION

The 10,000 kw gas-turbine power station has been built mainly for the purpose of studying problems associated with industrial applications of the gas turbine. The electricity generated will be consumed in

the Establishment, and thus help to reduce the import of power from the grid during peak periods.

The power plant consists of a two-line open-cycle gas turbine, with intercoolers and heat exchangers, operating at an overall efficiency of 41 per cent. The gas-turbine unit consists of a low-pressure and high-pressure stage, the low-pressure turbine driving the 11-stage axial-flow compressor (Fig. 2) at 2,800 r.p.m., and the high-pressure turbine (Fig. 4) driving the 13-stage axial-flow high-pressure compressor and the alternator at 3,000 r.p.m.

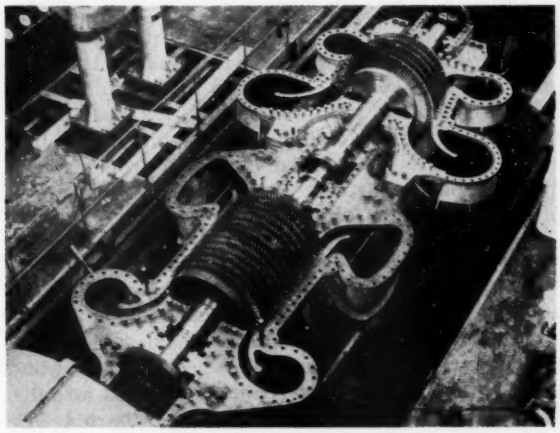

Fig. 4. The high-pressure compressor and turbine of the 10,000 kw Parsons turbo-generator with cover removed.

Air enters the low-pressure compressor at the rate of 208.6 lb. per second, and is compressed to 2.57 times its original pressure. After passing through an intercooler, where the temperature is reduced from 119 deg. to 32 deg. C., the air passes through the high-pressure compressor where it is compressed to 5.5 times its original pressure, the temperature thus being raised to 119 deg. C. The air is now passed through an air/gas heat exchanger, where absorption of heat from the exhaust gases heats the air to 308 deg. C., before being fed into the combustion chambers.

Liquid fuel is burned in the combustion chambers, and the hot gases, at a temperature of 650 deg. C., pass to and drive the five-stage high-pressure axial-flow turbine. The gases then enter the three-stage axial-flow low-pressure turbine.

The exhaust gases then pass through the air/gas heat exchangers, and are either discharged to atmosphere or through waste heat exchangers to supply hot water for site-heating.

Also installed in this building is a 750 kw Daniel Adamson pass-out steam turbo-alternator, which is capable of supplying the power required for starting the 10,000 kw gas-turbine set. Steam is supplied from the Battle test-house boilers at a pressure of 390 lb. per square inch, and steam at a pressure of 60 lb. per square inch may be passed out of the turbine and fed into the calorifiers which supply the site-heating system as an alternative to the 10,000 kw set's waste-heat recovery system.

OVERSPEED AND BURSTING RIG

Overspeed testing is carried out both as a guide to stress calculation and for proving new designs. The rig consists of two 300 h.p. 500-volt direct-current motors in tandem driving, through a 13-to-1 step-up gearbox, a high speed shaft. This shaft projects into a substantial reinforced-concrete test cell, in which rotors up to 6 ft. in diameter and 10 ft. in length may be mounted for overspeeding or bursting. In the latter case, the rotor is surrounded by a lining of packed cardboard to minimize damage to the fragments.

The driving motors are supplied by a 500 kw grid-controlled rectifier fed from a six-phase 11 kv transformer. Speed control at low speeds is effected by altering the phase of the input to the grid of the rectifier, and at higher speeds by weakening the field of the motors. By these methods, adjustment of speed to within 60 r.p.m. is possible over the whole range up to the maximum of 47,000 r.p.m. True speed is measured by an electromagnetic pick-up on the shaft, the signal being displayed on a cathode-ray oscilloscope and compared for frequency with the trace from a standard oscillator.

The plant, which is remotely operated from a control room, is provided with dynamic braking equipment to assist in bringing the motors, gearbox and high-speed shaft (together with what remains of the rotor under test) quickly to rest.

Rotors which require high power to drive them, for example, complete axial compressor rotors, can be run in an evacuated casing.

The primary purpose of the National Gas Turbine Establishment is to foresee and solve the problems that are likely to beset turbine manufacturers, and to suggest the most fruitful lines for future development. The Establishment also acts as an information exchange center between the various firms and it is

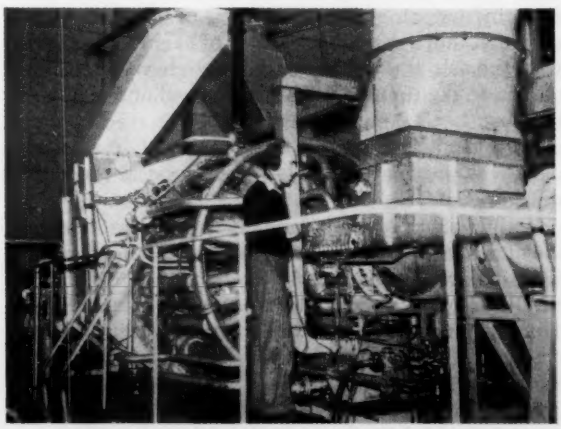

Fig. 5. The 1,000-kw Allen prototype gas turbo-generator set for major warships now undergoing endurance tests has run nearly 4,000 hours.

believed that the "pooling" of technical knowledge is one of the reasons why the British aircraft gas-turbine industry retains its leading position.

Although most of the effort at Pyestock is, perhaps, directed to the advanced problems of the aircraft gas turbine, work is also in progress on industrial and marine applications. In the Admiralty test house, two auxiliary gas turbines for generation of ships' electricity are now undergoing trials—the 1,000-kw prototype set for major warships constructed by W. H. Allen, Sons and Co., Ltd., Bedford, which has now run nearly 4,000 hours (Fig. 5); and a standard 750-kw Ruston and Hornsby turbo-alternator modified slightly for running on residual fuels. This latter installation, successfully run on gas oil, is now to be run on a residual fuel to assess the effects of corrosion and deposition.

RESIDUAL OIL BURNING

Also directed to the development of residual oil burning in industrial turbines is research on the suppression of inorganic ash formation.

Combustion of fuel oil droplets proceeds via distillation of the volatile constituents, leaving particulate carbon residues, containing the ash. With conventional tubular-type chambers, combustion of these carbon particles is substantially complete, and free ash is formed. The melting range of the ash is commonly 600 to 700 deg. C. and some of the constituents are volatile (e.g., vanadium pentoxide). During the passage of the exhaust gas through the turbine, ash may adhere to the turbine blades. At turbine temperatures between 500 and 600 deg. C., solid build-up of ash deposits occurs, interfering with the aero-dynamics of the turbine. At higher temperatures the molten ash fluxes away the protective chromic oxide layer on the turbine blade material (e.g., Nimonic alloys) and oxidation of the metal ensues, leading in time to the impairing of the mechanical properties of the alloy.

Means of overcoming these two sources of trouble lie in preventing the arrival of the ash particles at the turbine blade surface. This can conveniently be done by arresting the combustion process at a point at which there is still a quantity of carbon associated with the ash, thus giving a dry particle which cannot adhere to the turbine. Effective control of ash deposition has been demonstrated on a test rig for some conditions, and the penalty in terms of loss of efficiency as unburnt carbon need only be of the order of 1 per cent.

In the vortex type of chamber under development, the atomized fuel spray is ignited in a precombustion chamber where the volatile components of the fuel are burnt. The products then enter the vortex chamber where the carbon particles burn steadily as they proceed in a spiral path towards the center of the vortex.

Ideally, the radial position of a particle in the vortex is controlled by the centrifugal forces on the particle and the inward drag caused by the flow of gases. Thus, as the particle burns, its weight is reduced and it passes towards the vortex center. If particles of a uniform size can be supplied to the system, and if the flow of air is uniform, the particles can be exhausted at a uniform state of burn-out and this can be controlled by the rate of air flow and the temperature attained in the cyclone. These requirements have not yet been fully met but experimental work to achieve this object is proceeding.

The chamber design has been arranged to provide a very wide range of burning temperature and distribution of the air supply, so that the carbon-to-ash weight ratio in the exhaust can be varied at will. After preliminiary calibration on the test rig, this chamber will be run on the 750-kw Ruston and Hornsby gas turbine which is being tested by the Admiralty. In order to make it possible to adjust the internal form of the vortex chamber, a monolithic ceramic construction has been used. This also provides adequate cooling while using vortex outlet temperatures of the order of 1,400 deg. C.

COAL-BURNING GAS TURBINE

Ash deposits on the turbine blading form also one of the principal obstacles to the development of economical coal and peat-burning gas turbines for industry. To investigate this and other problems, the Ministry of Fuel and Power operates an ash-forming fuels laboratory within the National Gas Turbine Establishment.

The deposition of ash on blades may depend on the chemical composition and degree of pulverization of the coal; the temperature and rapidity of combustion; the efficiency of the fly-ash separator; the size and concentration of the dust passing through the turbine; the gas pressure, temperature and speed; the blade form and temperature. In order to separate the effects of these factors a flexible rig is being developed in which the variables may be altered one at a time. In this way a general picture of the mechanism of fouling will be built up.

The ash fouling rig at present consists of a small coal-burning chamber, a long-cone cyclone separator and a cascade of fixed blades to represent the turbine. An interesting feature is the fluidized coal feed to the combustion chamber through a feed-pipe of 3-16 in. internal diameter. Initially the effect of coal composition and sizing will be investigated on this rig.

Tests of a similar nature in which chemically inert dusts are being introduced into a hot gas stream before being passed over a cascade of blades are also being carried out to show up the physical rather than the chemical aspects of blade fouling.

AIR-COOLED TURBINE BLADES

Although the approach to the high-temperature gas turbine has been dictated primarily by military aircraft needs, N.G.T.E.'s successful work on air-cooled turbine blades and other components is likely

to play an important part in the industrial turbine field.

The major problem that in the past has impeded the development towards higher temperatures is that of cooling the very hot and highly-stressed turbine blades. Since the end of the war the National Gas Turbine Establishment has carried out much pioneer development work in this field which has culminated in the building and running of an experimental air-cooled turbine which has operated successfully at gas temperatures of well over 1,000 deg. C.

The development of blades with internal cooling surfaces and passages raises problems of manufacture. Among the methods that have been developed are the use of metal powders, using cadmium wires to locate the cooling air passages; when compacted in the furnace, the cadmium wires melt leaving free air ducts. The lost-wax process has also been employed for blade fabrication using silica tubes to locate the air ducts, these being subsequently dissolved by caustic soda. Extrusion and rolling methods have also been developed.

In parallel with the development of cooled blades a continuous effort is being made by sections of industry to develop new materials for turbine blades which might be capable of operating at much higher gas temperatures than at present without the necessity for cooling. There being relatively little scope left for spectacular development of heat-resistant metallic alloys, attention has turned in recent years to ceramic and cermet materials. So far, however, the inherent brittleness of such materials, which leads to rapid failure due to mechanical shock, and often by thermal shock, has proved to be a major barrier to their use for blading. Nevertheless, work in this field continues under the sponsorship of the Ministry of Supply and, in the marine engine field, under Pametrada.

A further problem arising in the high-temperature engine is that of cooling the hot surfaces in the combustion chamber and the turbine exhaust or jet pipe. For lightness, compactness, and general reliability some form of direct air cooling appears to be the answer. The most effective method found is that of "effusion" cooling, in which cool air is forced through an inner liner constructed of porous sheet material. To this end some promising work has been conducted at the National Gas Turbine Establishment towards the use of porous liners fabricated from closely woven and rolled wire mesh sheet.

THERMAL SHOCK

In the blading of aircraft gas turbines, conditions of rapid heating occur during take-off, while rapid cooling takes place during rapid deceleration, or in the event of an accidental fuel cut. The thermal shock is greater the higher the blade temperature. In uncooled engines, the gas and therefore blade temperature is progressively increasing in order to obtain higher thrusts, and so thermal shock tends to become more severe. A study of the factors involved and the effects produced therefore becomes increasingly necessary.

Such a study is in progress at the National Gas Turbine Establishment on ceramics and cermets (ceramic-metal mixtures) potentially useful for gas turbine blading, as well as on metallic alloys. Its main objects are to investigate the progressive damage and the mechanism of failure, and to determine the factors governing resistance to thermal shock. In the test rig, blade shapes are mounted in cascade and can be rapidly heated in high-velocity high-temperature gases followed by rapid cooling in high-velocity air at controlled rates and at pressures up to 10 atmosphere. To obtain the desired conditions of heat transfer, the cooling air is blown upward through a fluidized bed of fine powder.

Laboratory techniques have also been developed for the application of thermal shocks of controlled severity. Theoretical determination of the stresses from calculated temperature distributions have been made for simple shapes, e.g. cylinders; for a complex shape such as a turbine blade, advanced mathematical techniques are necessary. If the differential equations involved can be programed for solution by automatic computing machines, it will be possible to recommend changes in blade shape that will reduce susceptibility to thermal shock failure. It is hoped the overall results of this study will provide information that will assist in the "design" of thermal shock-resistant materials for gas-turbine blading.

INTAKE DESIGN AND BLADE VIBRATION STUDIES

To study the effects of density changes on the performance of an axial compressor, a variable-density compressor rig is in service. The air passing through a model compressor under test is confined to a closed return circuit. The pressure in the circuit can be reduced to 0.1 atmosphere or increased to 4 atmospheres. A water cooler in the circuit keeps the air temperature constant, but no refrigeration is available. All the air in the closed circuit is dried.

The compressor under test is driven by an independent air turbine. The maximum speed is 30,000 r.p.m., giving a blade tip speed of 1,300 ft. per sec.,—well above current practice. The rig is controlled from a central control room. To keep testing time to a minimum, all readings are recorded photographically.

The rig has been used for a comprehensive series of tests into the effect of altitude on a single-stage compressor. It has also been used to study the loads on blades in a compressor due to vibration. A program of work, in which the intake conditions to the compressor are varied in a manner similar to that expected at very high aircraft flight speeds, has just been completed. The rig is now being used for another blade-breakage investigation. Afterwards it is planned to examine the performance of a compressor designed for very high rotational speeds. A low air density will be used to reduce the blade loading as a safety measure.

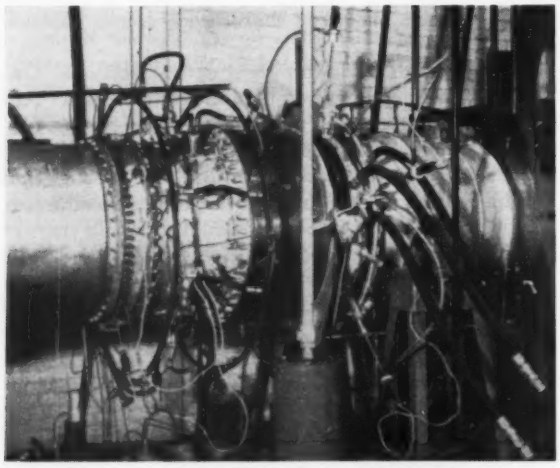

Fig. 6. Annular combustion chamber test rig.

TESTING COMBUSTION SYSTEMS FOR TURBINE ENGINES

In the past, common practice has been to use a number of "can" type combustion chambers, grouped around the central spine of the engine. Such an arrangement does not make the best possible use of space and weight, and the annular type of combustion chamber is now gaining favor (Fig. 6).

This necessitates an increase in the size of test plant required for the development of the combustion equipment since the whole annular chamber has to be tested whereas, with can-type chambers, it is sufficient to test one "can." Because the large air supplies required are not readily available at the manufacturers' facilities, annular combustion chambers are at present being tested mainly at Pyestock. The combustion chamber is first tested at pressures a little above atmospheric in order to correlate the performance as installed on the test rig with that previously determined by the manufacturer; the tests would then be continued to sub-atmospheric pressures to determine the effect on efficiency and stability (that is, the range of fuel-to-air mixtures that can be burnt) and on ignition characteristics. To obtain these conditions the plant air supply must be switched to drive ejectors which will draw off the combustion-chamber exhaust gases and reduce the pressure level in the combustion chamber. By suitable throttles and the use of by-pass pipes it is possible to control both the air pressure level in the chamber and the rate of air flow through it.

This rig is comprehensively protected against the danger of explosion: the fuel supply to the rig is automatically cut off (i) if the water blanket inhibiting the exhaust duct should fail; (ii) if the air supply should fail; (iii) if the flame, detected by an infrared cell, should become extinguished.

The air pressure and flow and the rate of fuel supply have to be measured accurately, as does also the temperature at inlet and outlet from the chamber, in order that the efficiency of the burning process can be determined. Additional information on combustion efficiency can be obtained by chemical analysis of the exhaust gases. It is in fact necessary to determine the pattern of temperature distribution at the outlet section, both in order to obtain a representative mean value and also to ensure that the distribution is sufficiently uniform. Hot zones in the exhaust can result in mechanical damage to the turbine, which must follow the combustion chamber, and a stratified temperature distribution can result in a loss of aerodynamic efficiency in a turbine designed to accept a uniform distribution.

RAM-JET ENGINES

A ram-jet, essentially an engine for supersonic flight, has an air intake which scoops up a steady stream of air and slows it down to subsonic speeds, increasing the pressure and density of the air as it does so by the conversion of kinetic energy into pressure energy. Much of this conversion of energy is done through the agency of shock waves, the efficiency of the process being largely determined by the complexity of the shock pattern employed. Thus the family of inclined shocks created by a spike in the center of the intake results in a greater pressure recovery than the single "bow-wave type" normal shock which forms in front of a plain-hole, or Pitot type, intake. The ram pressure ratio which can be obtained from an intake system increases rapidly with flight speed, so that while it is only possible to get a pressure ratio of about 1.8 when flying at the speed of sound, at three times this speed, say 2,000 m.p.h. in the stratosphere, a ram pressure ratio of 36 is theoretically available.

In this high-pressure air, normal fuel, such as kerosene, is burnt to raise the temperature of the air to the vicinity of 2,000 deg. C. Although some pressure is inevitably lost in this heating process, the heat energy added is such that when the hot exhaust gases are allowed to expand again through a correctly-shaped propelling nozzle they reach a velocity considerably greater than the velocity the air had when approaching the engine. Thus a given mass of air in passing through the engine is accelerated rearwards and the engine consequently experiences a reaction "equal and opposite to" this force.

There are thus no rotating parts in a ram-jet engine, apart from the fuel-pumping system which often runs from a miniature air turbine operating on ram pressure. One penalty paid for this sweeping simplification is the inability of the engine to produce any thrust until the flight speed is sufficiently high for worthwhile ram compression to be achieved. With a ram-jet designed for flight at speeds of the order of Mach 2, this lower limiting speed is about one and a half times the speed of sound, and below this speed some alternative means of propulsion must be provided. For a pilotless missile the obvious choice for this launching "boost" falls on quick-burning solid-fuel rockets which can be disengaged from the missile when a satisfactory speed has been reached.

A further penalty is in the size and cost of test

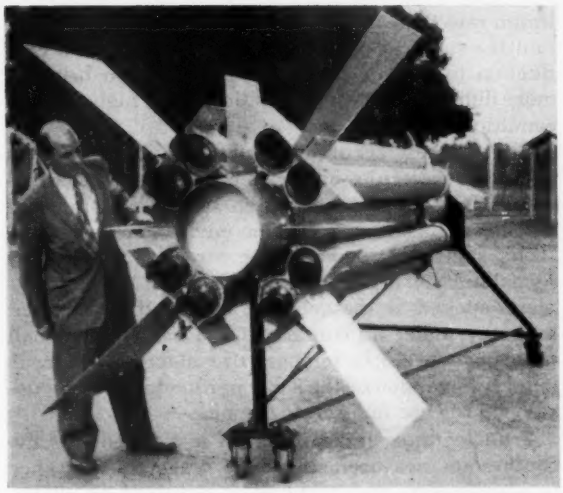

Fig. 7. Ram-jet test vehicle, launched by solid-fuel rockets which are jettisoned when the vehicle has attained sufficient speed for the ram-jet to sustain itself. Instrument readings are transmitted to the ground by radio.

equipment required for the development of ram-jet engines. From the nature of the engine it can only be tested either by flying it at supersonic speeds or else by simulating on the ground the extremely high air velocities and the low atmospheric pressures to which the engine is subjected in flight. In fact both methods of testing have to be used. Fig. 7 shows a telemetering test vehicle for flight-testing ram-jets, using detachable rockets to launch the vehicle.

Full-scale combustion chamber development is usually carried out by mounting the ram-jet combustion chamber at the end of a duct directly connected to the plant air supply. In this type of test the best forms of fuel injection and flame stabilization equipment can be established provided that representative air flow conditions can be reproduced. By conducting these tests at air pressures of 40 to 50 lb. per square inch absolute, corresponding to supersonic flight at fairly low altitudes, the combustion equipment can be subjected to mechanical loadings comparable with the worst flight cases.

By fitting powerful hydraulic jacks to the valves controlling the air supply it is possible to reproduce the rapid rise of both air pressure and air flow which occur during the rocket launch of a ram-jet, and in this way fairly representative ignition trials can be carried out.

To test the combustion chamber at conditions corresponding to high altitude, where inevitably the problems of combustion are worse, even though problems of mechanical reliability are lessened, it is necessary to provide exhauster plant which can draw air through the combustion chamber at pressures considerably below sea-level atmospheric pressure.

In the free-jet wind-tunnel the complete engine is placed in a high-velocity air stream issuing from a convergent-divergent nozzle. Such a nozzle can be made to give a parallel air stream of effectively constant supersonic velocity, and provided that the engine intake is completely submerged in this stream, leaving some air to spill over the outside of the engine, the air flow within the engine can be assumed to be identical to that occurring in flight at the Mach number of the free air stream. Methods for varying the velocity of the free-jet air stream are in course of development, but are not yet in use.

FREE-JET ALTITUDE CELL

Although existing test plant is not adequate to test a full-size ram-jet at free-jet air speeds simulating Mach 2 flight, the problems involved can be studied by using smaller models. The high pressure ratio required to produce a high Mach number free-jet is obtained by letting the jet exhaust into a region of sub-atmospheric pressure.

This is accomplished in an altitude test cell; a cylindrical chamber is connected at one end to an exhauster plant which maintains the pressure in the chamber at the required sub-atmospheric value. At the other end of the chamber air is delivered into the cell through a shaped nozzle which gives a jet stream of the required velocity blowing at the intake of the test model. In this installation flight at speeds up to Mach 2 and altitudes up to 40,000 ft. may be simulated.

The model is attached to a removable lid through which pressure tappings and other control and instrumentation equipment pass. The axial direction of the free-jet may be altered manually during running to simulate yawed flight. The shock-wave pattern at the intake may be observed and photographed during operation by means of a shadowgraph and spark-illumination system. The tests are conducted from the adjacent control room, and the readings may be recorded photographically.

A free-jet cell of this type enables the performance of intakes and combustion systems under simulated free flight conditions to be assessed, while the operation of the engine is under direct and constant control, and observations of performance may most readily be made.

Other investigations in progress at N.G.T.E. include research on the mechanism of spontaneous combustion; the response of turbo-jet control systems to rapid adjustments to fuel flow; the behavior of convergent-divergent propelling nozzles for supersonic flight over a range of flight conditions; and a research compressor designed to operate at slightly supersonic blade speeds, to enable detailed flow patterns to be studied with a view to raising the speed at which the compressor efficiency drops off as a result of shock formation.

TEST INSTRUMENTS

In conclusion, it is interesting to refer briefly to some of the special test instrumentation in use at Pyestock.

Fuel/Air Ratio and Combustion Efficiency Meter. —For determining the fuel/air weight ratio and the

combustion loss, an exhaust-gas analyzer is at an advanced stage of development. A sample of combustion gases is subjected to a two-stage process. Firstly, the gases are completely burnt over platinum and copper oxide, and the resultant gross carbon dioxide content is measured by means of an infra-red gas analyzer. Secondly, an identical sample is passed through a freezing trap to remove condensable constituents (fuel and water), and the net (existing) carbon dioxide, carbon monoxide, and hydrogen are measured by two infra-red gas analyzers and a sonic analyzer, respectively.

From these four quantities the required data can be calculated. A measurement takes some five or six minutes to complete. Measurements can be made at any fuel/air ratio up to 0.125 to 1 and at any combustion loss up to 100 per cent. (i.e., an unburnt fuel-air mixture). Means are provided for pumping sample gas from combustion systems running at simulated altitude conditions up to 50,000 ft., maximum r.p.m.

Circular Time-Base Speed Control.—In research on gas turbines, the accurate control and measurement of rotor speeds is of great importance. One method, at present under development, is the instantaneous comparison of the frequencies of electrical signals from a tuning-fork (constant frequency) and a small alternating current generator coupled to the rotor shaft (frequency variable with speed). The presentation, on a cathode-ray tube, is a pattern resembling a cogged wheel, stationary when the two frequencies are identical or in an integral ratio, and otherwise rotating clockwise or anticlockwise. The aim is the maintenance of a stationary pattern, and the rotational presentation of an error in speed helps an operator to make instinctive manual correcting adjustments to a wheel control valve on, say, the compressed air supply to a turbine.

Suction Pyrometry.—For measuring gas temperatures, thermocouples are usually used; to bring the wires to gas temperature involves getting the maximum rate of heat transfer from gas to thermocouple and the smallest possible loss by radiation and conduction to the surroundings. The problem becomes more difficult at low gas densities under high altitude conditions.

The greatest accuracy is obtained by having as many gas molecules as possible striking the thermocouple in a given time, at the same time shielding and insulating it from cooler environments. In the "sonic suction pyrometer," the wires are fixed across a small nozzle, in a tube, through which the gas sample is sucked at the speed of sound. It gives great accuracy under all conditions and has a very small time lag when gas temperature changes occur. A miniature version of the sonic pyrometer is being developed for use in aircraft engines.

Tip Clearance Indicator.—An instrument for the continuous measurement of the blade tip clearance in compressors and turbines is required on turbomachinery used in research, (*a*) for mechanical reasons (i.e., blade creep, thermal distortion, etc.) and (*b*) for accurately assessing all factors influencing the performance.

The probe unit, which consists of an electric motor and gearing, is mounted outside the compressor (or turbine). It slowly feeds an electrically insulated and charged probe towards the rotating blading. When the charged probe is within approximately 0.001 in. of the orbit of the largest blade, a spark passes and the amplifier reverses the motor to withdraw the probe a small distance. When no further sparking takes place, the probe with its condenser again fully charged allows the amplifier to reverse the control motor and the re-charged probe once more approaches the rotating blading. The probe thus hunts between sparking and not sparking on the blading.

A counter which is coupled by synchronous electrical links to the probe unit follows the movements of the probe to give a continuous reading of the gap between the fixed and rotating components.

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ENGINEERING ABSTRACTS

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1–56	Fresh Water from Salt Water
2–56	Comparison of Six Lubrication Methods
3–56	Nuclear Energy Today
4–56	Condensed Review of Some Recently Developed Materials
5–56	Heat Problem Seen as Block to Power Increase in Diesels
6–56	Forum on Hydraulics
7–56	Millions of Balls—Millionth Tolerance
8–56	Single-Car Locomotive of 3,300 HP
9–56	Photocopy Techniques for Engineering Records
10–56	Applications of Vibratory Energy
11–56	Electrochemical Recorder for Dissolved Oxygen in Boiler Feed Water
12–56	Aluminum for Transformer Windings
13–56	Radio-Frequency Interference a Problem of Automatic Machine Control
14–56	Explosion Meter Evaluated
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16–56	A Photo-Electric Automatic Flame Cutting Machine
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21–56	A 10,000—SHP Gas Turbine Ship: Proposed Installation for a Merchant Vessel
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26–56	Cleaning Tool for Pistons in Diesel Locomotive
27–56	Mechanism of Convective Heat Transfer and its Role in Gas Turbines
28–56	PWR Power Plant

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1–56 "Fresh Water from Salt Water"—D. J. Neville-Jones, Research and its Application in Industry, V8, n. 11, Nov. 1955, pp 423–429. Industrial demands for water have been steadily increasing in many areas throughout the world. In coastal areas this may lead to sea water infiltration as increased pumping lowers the level of underground reserves. Cooperative work on subject was started by Netherlands in 1951 and is now being carried out in Europe, United States and North Africa. Methods under investigation and cost of producing water include:

Process	Cost (from sea water) $/acre-ft.
Solar energy for multiple evaporation	700–1069
Simple solar evaporation	400–775
Triple effect distillation	700
Vacuum distillation with waste diesel heat .	528
Vapor compression distillation	429
Ten effect distillation (actual $)	415
Super critical distillation	114
Electrolytic membrane (885 p.p.m. feed) ...	4

Work in the United States on distillation in the supercritical state, at 700°-900°F. and pressures between 3000 and 5000 psi is most interesting. There is no distinction between liquid and vapor at the critical point of pure water. Salt added to water results in a solution phase with a critical temperature greatly different from pure water. Thus saline water has two phases at values of temperatures and pressures above the critical values for water. In this method separation is simple and with efficient heat exchange the net

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energy requirement for the process is small. The plant required appears to consist only of turbines, a heat exchanger and a separator.

2–56 "Comparison of Six Lubrication Methods"—Beno Sternlicht, Product Engineering, V.26, n.13, Dec. 1955, pp 183-188. Lubricant is required to: provide cooling medium in bearings; or decrease friction between elements; or support load by developing hydrodynamic pressure. Six methods are discussed with their applications, advantages and limitations. The methods are: forced feed, oil-ring, wick, mist, oil jet and cross feed. Methods are illustrated. Section on background material is included.

3–56 "Nuclear Energy Today"—L. N. Rowley and B. G. A. Skrotzki, Power, V.99, n.12, Dec. 1955, pp 74-96. This article includes: Description of how reactors work, reactor types, pressurized water reactors (PWR), boiling water reactors, sodium graphite reactors, fast breeder reactor, homogeneous reactor, and fuel preparation; nuclear power plant elements, reactor accidents, fuel handling, shielding, heat exchangers, coolant pumps, electromagnetic pumps; reactor programs including five year reactor development program, power demonstration reactor program, private license application and special projects. Diagrams and artists' drawings illustrate the various plants and components under discussion.

4–56 "Condensed Review of Some Recently Developed Materials"—Machinery, V.62, n.2, Oct. 1955, pp 170-185. This review lists 139 materials, trade names in alphabetical order, properties, applications and includes manufacturers. The materials include: aluminum alloys, polyester resin, lubricants, rustproof coating, brazing alloys, fluxes, paint stripper, metal filler, welding rod, rust preventative, metal-containing resin, floor armor, phenolic resin, protective coatings, beryllium-copper alloy, structural adhesives, nickel-chromium-silicon alloy, solvent degreaser, stainless steel, solder, belt preservative, hard facing alloy, core materials, dry-film coatings, anti-sieze sealant, cutting oil, magnesium, spring alloy, water reducible paints, die steels, vacuum melted alloys, sintered carbides, tubing, lubricating process, cemented carbides, resin impregnated wood, drill blanks, tungsten alloy, glazing material, leaded steels, photographic paper, aluminum metalizer, plastic tooling material, fiberglass, industrial adhesive, plastic metal laminate, aluminum compound, penetrant dye, pulley-lagging material, baked protective coating, aluminum etchant, electrocleaning material, coating material, tooling compound, silver alloy sheets, titanium fasteners, copper dipping process, casehardening compound, metal powder, polystyrene plastic, floor coating, paste solder, drawing compound, lock-nuts, chromium-iron alloy.

5–56 "Heat Problem Seen as Block to Power Increase in Diesels"—Heinrich Schneider, Diesel Progress, Dec. 1955, pp 44, 46, 47. An empirical factor (Heat Factor) has been established for comparing heat load of various diesel engines. This heat factor (HF) equals the cylinder diameter (D), times the mean effective pressure (MEP), times the revolutions (RPM), times C (equaling ¼ for four-cycle engines and ½ for two-cycle engines), times a constant K. Various engines are compared as to HF. Engines operating continuously have HF below 100 per cent, based on HF of 3.0 as 100 per cent. Engines for intermittent operation have HF 100-125 per cent. Factors having bearing on engine life are discussed.

6–56 "Forum on Hydraulics"—Mechanical Engineering, V.77, n.12, Dec. 1955, pp 1056–1064. The turbo machinery compressor is discussed under the following headings: strength problems; flow processes; areas to be studied; axial flow compressor. The hydraulic prime movers section includes: hydro plants of the future; turbine developments. Water hammer: review of past, present and future work. Centrifugal pumps: size and speed; industrial processing pumps; problems of cavitation; problems of higher pressures. Cavitation phases included are: nature of the phenomenon and future work.

7–56 "Millions of Balls—Millionth Tolerance"—Edwin H. Goodridge, Jr., Machinery, V.62, n.4, Dec. 1955, pp 143-151. Production of 5,500,000 high-carbon chromium-steel and stainless-steel balls, from 0.025 to 1⅞ inches in diameter per day is described. Heat treating, machining, grinding, finishing, lapping polishing and inspection methods are presented.

8–56 "Single-Car Locomotive of 3,300 HP"—The Oil Engine and Gas Turbine, V.23, n.269, Mid Nov. 1955, pp 246-248. The most powerful single-car diesel locomotive in the world has completed its trials in the North of England. It is to carry out other trials on tracks of the British Railways starting in passenger service. This locomotive, the Deltic (type Co-Co), weights 106 tons. It has a maximum design speed of 90 mph but it can be geared for higher speeds. Two Napier Deltic engines are installed in the locomotive and develop a total of 3300 bhp. The ratio of weight to power is 72 lb. per horsepower. This Deltic engine has been proven in motor torpedo boats and other applications. Engine data are as follows: 18 cylinders per engine; two stroke opposed piston; bore and stroke 5.125 in. by 7.25 in. respectively; traction rating both engines 3300 bhp at 1500 rpm; cylinders arranged in three banks of six each; main output shaft rigidly connected to the main generator shaft.

9–56 "Photocopy Techniques for Engineering Records"—Spencer R. Griffith, Machine Design, V.27, n.12, Dec. 1955, pp 151-154. Three examples are presented showing the use of photocopy techniques for simplification of drafting and records problems at a large company concerned with military production over the past five years. Photocopying has completely replaced redrafting and is also used for making copies of administrative documents.

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10–56 "Applications of Vibratory Energy" — Arnold Graves; Engineering, V.180, n.4684, Nov. 4, 1955, pp 637-639. An apparatus, using vibratory energy, to determine elastic moduli of materials is described. The instrument, in one form, consists of a crystal-frequency standard oscillator, an output amplifier, a vibrator or transducer, a pick-up and amplifier with meter to indicate when the resonant frequency of the test specimen has been reached. An operator can, with little experience set up a specimen and determine its modulus of elasticity with great accuracy in a matter of minutes.

11–56 "Electrochemical Recorder for Dissolved Oxygen in Boiler Feed Water"—The Engineer, V.200, n.5208, Nov. 18, 1955, p 735. Dissolved oxygen in boiler feed water can be measured with an electrochemical recorder. This instrument is suited for use on modern boilers where the high temperature and pressure aggravates the effects of small quantities of oxygen on life of boiler tubes. The analyzer which is the basis of the recorder uses the polarographic principles. Operation is based on the fact that if a small potential difference is applied between two electrodes immersed in water, which is conductive, the current flow is proportional to the concentration of reducible substances in the water. Two such cells are used with different values of potential difference so two currents can be obtained, one proportional to concentration of certain impurities and the other proportional to these impurities plus the dissolved oxygen. By a recording of the differences in currents a measure of the dissolved oxygen is obtained.

12–56 "Aluminum for Transformer Windings"—Power, V.99, n.11, Nov. 1955, pp 95-97. Aluminum-strip windings with anodic coatings as turn-to-turn insulation offer possible savings in dollars as well as providing more compact transformers. Anodic coating is now proposed as an insulation that would replace paper, glass or enamel. The anodic coating is an aluminum oxide which is an excellent resistor and has a higher melting point than aluminum. Anodic film is a hard inelastic coating and is built up to 0.0003 in. This film presents a problem due to crazing when the coated conductor is bent. Use of anodic coated thin strips can eliminate voids which make up to 25 per cent of space where round conductors are used. A minimum bending radius of 0.5 in. is recommended. Temperature limits have not yet been established. Various manufacturers are now investigating the use of anodic coated aluminum strips for transformer windings. Final results are not yet available.

13–56 "Radio-Frequency Interference — a Problem of Automatic Machine Control"—Charles D. Emerson, American Machinist, V.99, n.23, Nov. 7, 1955, pp 122-125. Radio-frequency interference, RFI, takes many forms and can be caused by a wide range of electrical devices. A military specification MIL-I-19610 was created to deal with RFI to insure that new equipment will not interfere with military communications. Sources of RFI include: commutator motors, bells, buzzers, limit switches, fluorescent lamps, and control devices. Non-offenders include: electric meters, manual circuit breakers, voltmeters, welding panels, engine starters, and power switchboards. Only about 10 per cent of machine tools bought by the Navy in the past year were affected by RFI restrictions. Aside from communications, electronic computers are extremely vulnerable. Fluorescent lamps have caused trouble on computer operations. As automatic machine tool operation is controlled more by magnetic tape programming RFI will become a more serious industrial problem. RFI can be reduced by proper design or shielding.

14–56 "Explosion Meter Evaluated"—J. E. Johnson and J. W. Crellin; Bureau of Ships Journal, V.4, n.7, Nov. 1955, pp 8-10. In estimating the degree of hazard due to explosive vapors given off by gasoline, other fuels and solvents, the explosion meter is used. Operation consists of drawing a sample of air from a compartment through the catalyst chamber in the meter. When fuel or solvent vapors are present the catalyst causes them to react with oxygen and the amount of heat developed is indicated by a needle deflection on a dial. Care is essential in using a meter. Operating instructions should be followed. Special meters may be required for use with certain fuels. The Navy uses a modified meter for testing leaded gasoline vapors. The catalyst in a regular meter would be quickly poisoned by the tetraethyl lead. Hydrogen gas concentration of dangerous values requires a special meter. A meter will react differently with various fuels. A meter calibrated for proper readings for gasoline reads low when used to test vapors of heavier fuels. Tests conducted by the Naval Research Laboratory show low responses by explosion meters to vapors of heavier fuels. Tests were made on JP-5 and diesel fuels. Two refineries also show that explosion meters used for specification tests read low. Conclusions are: data show explosion meter gives low readings for explosivity of JP-5 and diesel fuel; specification test of method 1151.1 of Federal Specification VV-L-79le can be expected to report erroneously low values for these fuels at 125°F, more reliable tests can be devised; the explosion meter is a valuable tool for assessing explosion hazards if the type of gas or vapors is known and suitable corrections made.

15–56 "Improvements in Nitriding" — G. Keller; The Engineers' Digest, V.16, n.11, Nov. 1955, pp 521-522. Nitriding as a means of surface treatment has not been used to the greatest extent. Sharp dimunition in hardness through the nitrided layer has been a serious handicap. This has been particularly true where the work piece must be final ground. New techniques now permit the hardness of the outer layer and the depth of the nitrided layer to be controlled. Research work conducted at the Swiss Federal Ordinance Factory in Berne led to discovery of the means for this control.

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16–56 "A Photo-Electric Automatic Flame Cutting Machine" — The Marine Engineer and Naval Architect, V.78, n.947, Oct. 1955, pp 375-378. This machine, the Schichau Monopol automatic flame cutter, permits production of accurate profiles in complex shapes in steel plate by employing photo-electric scanning of precision photographic negatives. The equipment consists of a control console that travels along an accurately planed bed which is carried on leveling screws. It contains a fixed lead screw. The console is propelled along the lead screw by a rotation nut. The cutting heads are carried on a welded aluminum alloy span which extends from the console. Drawings are prepared on sheets of aluminum foil faced on both sides with special paper that is moisture proof and has a contraction of 0.002 mm per m per 10°C. Negatives are made by Gevaert on glass plates with a coefficient of expansion of 0.000006 mm over the range from 0° to 100°C. The negative will expand due to local heat in the machine which may cause a 20°C rise. This rise can result in a theoretical error of 0.057 in. in 12m. Industrial burning heads are used. In operation the negative is mounted in a special carrier and then placed in the control console. A beam of light is projected through the negative, clear lines, to a photoelectric cell. The control principle requires the negative and its holder to be guided in such manner that the light passes through the clear lines. The negative and carrier move to provide the scanning control. Two similar profiles can be cut at the same time. The machine can cut about 84 ft. per hour with one burner and 168 ft. per hour with two burners. This is roughly three times the cutting by orthodox methods. A prototype machine has worked for two years on a two shift basis with a utilization factor of 97 per cent.

17–56 "British B.E. 25 Is a 'Supercharged' Turboprop"—S. G. Hooker; SAE Journal, V.63, n.12, Dec. 1955, pp 34-37. The B. E. 25 is a twin spool turboprop engine designed to replace the Proteus 755 turboprop in such aircraft as the Britannia. In the B. E. 25 the high pressure compressor, the combustion chamber and the high pressure turbine form a unit similar to the single spool jet engine. Its exhaust drives the high pressure turbine which supplies power to drive the low pressure compressor and the propeller through reduction gears. The specific fuel consumption at 1340° F. T.E.T. with a compression ratio of 10:1, is 0.37 lb. per hp-hr at 25,000 ft. and 300 mph. Both compressors are constructed entirely of steel. Nuts, bolts and chunks of ice have passed through the compressor with no catastrophic failure. Combustion chamber design is based on the Proteus. The turbine blades are shrouded on the first three rows.

18–56 "How to Prevent Fatigue Failures" — Joseph Viglione; Product Engineering, V.26, n.10, Oct. 1955, pp 174-178. Faulty workmanship or poor design cause most fatigue failures. Fatigue failures result from repeated loads at stress values well below those that cause failure under static conditions. These failures, fractures, are usually characterized by a progressive smooth area originating at a stress raiser where concentric markings start and then an area that is rough and of a bright crystalline structure. Causes of fatigue failures include: poor design, poor workmanship, sharp notches, small holes, V notches, fillets of small radius. Surfaces that are smooth, generally speaking, have a greater resistance to fatigue than rough surfaces. Cold working, shot peening, carburizing, nitriding and cyaniding improve fatigue resistance of steel parts. Surface coatings, metallic type, generally reduce fatigue strength of steel parts. Chrome and nickel plating may reduce bending strength of steel by 10 to 40 per cent. Softer platings such as zinc and copper have little effect on fatigue strength. Hot dip galvanizing may reduce fatigue strength of steel by 40 per cent. Corrosion and inclusions can set up stress raisers and lower fatigue strength. Load application frequency is not important at speeds under 30,000 repetitions per minute. Prestressing can increase the fatigue strength of steels if done properly.

19–56 "The Solar Battery"—Gordon Raisbeck; Scientific American, V.193, n.6, Dec. 1955, pp 102-104, 106, 108, 110. The first application of a solar battery is being made by Bell Telephone Laboratories at a repeater station on a rural telephone line near Americus, Ga. This battery, mounted on top of a telephone pole generates several watts of electricity during sunlight hours. Power that is not used is stored in a storage battery to supply power at night and on cloudy days. Interest has been great in development of means to harness the power of the sun. In two days the earth receives in sunlight more energy than contained in all the known reserves of fossil fuels. Conventional photocells deliver as power only 1 per cent of the light energy they absorb. The new solar battery is 20 times more efficient. It will generate electric power from sunlight at the rate of 90 watts per square yard of illuminated surface. The solar battery is impractical to supply needs of the average home. Storage batteries to cover night and cloudy weather power needs of the average home would cost initially about $5,000 and $1,000 per year to maintain. As the solar battery is developed it will likely open up entirely new fields of use. At present immediate applications appear possible in telephone, telegraph, radio and television—where the power need is small but often in remote locations where no power lines are located.

20–56 "The M. A. N. 'Whisper Engine' "—Dexter Craig; Diesel Progress, Oct. 1955, pp 22-24. The revolutionary fuel injection system developed by Dr. J. S. Meurer has resulted in quieter operation while producing normal horsepower, little smoke, remarkable tolerance for various kinds of fuels and excellent economy. The new M. A. N. engine is so quiet in operation it has been named the "Whisper" engine. In the "Whisper" engine the fuel is injected in two solid streams directly onto the combustion chamber walls. Fuel is thus permitted to spread over about half the area of the

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combustion chamber with a small portion projected into the open chamber to serve as the combustion starter. Meurer theorizes that in the "Whisper" engine fuel is spread in a thin layer over a large portion of the combustion chamber at a controlled temperature. It then vaporizes with minimum exposure to oxygen, evaporating before mixing with oxygen and igniting by inflammation instead of auto-ignition. More complete burning is achieved. Descriptions of injection, piston cooling and combustion are presented. (also see p. 154.)

21–56 "A 10,000—S H P Gas Turbine Ship: Proposed Installation for a Merchant Vessel"—The Motor Ship, V.36, n.428, Nov. 1955, pp 352-354. A gas turbine propulsion plant is described for a merchant vessel. Two 5,000 shp gas turbines driving through pinions to a common gear box are proposed. The high pressure and low pressure turbines drive high pressure and low pressure compressors respectively; power is taken from a free power intermediate pressure turbine. An intercooler and a heat exchanger of 70 per cent effectiveness are used. Reheating is applied between the high and intermediate pressure turbines. The reheating reduces air rate by 33 per cent and increases thermal efficiency by 10 per cent. Overall pressure ratio is 13.6 and maximum turbine inlet temperature is 1250° F. Life of 100,000 hours is the design value. Specific fuel consumption (main engines only) is 0.474 lb/shp-hr and increases slightly down to 50 per cent power. Astern power will be provided through fluid couplings and astern converters of the Pametrada design. Heavy fuels would be burned after proper treatment. Initial cost of the gas turbine would be about 6 per cent greater than for a steam turbine plant. Maintenance costs would be lower for the gas turbine than for either the steam turbine or diesel plant due to the comparatively few auxiliaries. The gas turbine plant could deliver power within 20 minutes from a cold plant.

22–56 "Integral Seal Ball Bearings"—Carter T. Bragdon and Michael T. Monich; Product Engineering, V.26, n.12, Nov. 1955, pp 179-185. Integral seal ball bearings simplify assembly by reducing number of parts and eliminating relubrication, and save weight and space. Seals must be selected with consideration for speed range, type of lubricant, contaminant to be excluded, operating temperatures, mounting position and life. Integral type ball closures are divided into two types: contact and clearance. Materials used for closures include: felt which will withstand temperatures up to 275° F. before charring; synthetic rubber which has low friction, low permanent set, is nonabrasive, can be precision molded, and can be bonded to metal. Buna-N will stand continuous temperatures up to 225° F. while special polyacrilic rubber will operate up to 350° F. Life of grease is a function of the rate at which it oxidizes. High ambient temperatures often dictate grease life. Silicones are among the best high temperature greases. Curves are included to show effect of temperature on grease life and speed correction factors. A probability curve is used to illustrate statistical analysis techniques. Although types of sealed bearings vary, the most widely used is the single row radial which is known as the Conrad or deep groove type. Current trends are toward higher speeds and elevated temperatures. Flexible synthetic sealing materials with low friction characteristics are needed to operate at 500° F. and above. Teflon and silicones will withstand this temperature, however, it is expensive and is too stiff to be an effective sealing element. Silicone rubber is used successfully in many applications. Research on greases will play an important part in future developments.

23–56 "Electronic Virbration Analysis"—James E. Rhodes; Machine Design, V.27, n.11, Nov. 1955, pp 193-194. A portable vibration analyzer consisting of a hand-held seismic pickup with filtering probe, a stroboscopic light and cabinet with electronic circuits which transmit vibration data from the pickup to panel meters showing displacement and frequency, has been developed. This analyzer does not require removal of individual parts or subassemblies from a machine for separate analysis. Vibrations with displacements as small as 0.000001 inch are detected and frequency range is from 500 to 160,000 vibrations per minute. This analyzer is used to check balance tolerances on high speed grinders.

24–56 "Honing Techniques Control Size"—Glen M. Calvert; The Tool Engineer, V.35, n.5, Nov. 1955, pp 91-94. Recent developments in honing and honing equipment may soon make selective fitting of pistons in engine cylinder bores unnecessary. Cylinder bores are now being finished uniformly within 0.0005 inch for size and with required total taper of 0.0005 inch. Savings have been realized by reduction of scrap to amortize the new equipment within six months.

25–56 "Commonwealth Edison's Nuclear Power Plant"—Titus G. LeClair and Samuel Untermyer; General Electric Review, V.58, n.6, Nov. 1955, pp 19-22. A contract was signed on July 22, 1955 by General Electric and the Commonwealth Edison Company calling for GE to build a 180,000 kw dual-cycle-reactor generating plant at a cost of $45,000,000. This plant, The Dresden Generating Station, located 47 miles southwest of Chicago, Ill., is scheduled for completion in 1960. The Dresden plant will generate power at about one cent per kilowatt-hour. A modern fossil-fuel plant generates power at about three fourths of a cent per kilowatt-hr. The Dresden plant will cost $250 per kilowatt while a conventional steam plant costs $167 per kilowatt. This plant will provide information for the design, construction and operation of future nuclear plants that will be competitive with the modern steam plant.

26–56 "Cleaning Tool for Pistons in Diesel Locomotive"—Diesel Progress, Nov. 1955, p 33. A leading midwestern railroad has reduced the cleaning cost on every piston 80 per cent by use of a vapor blast

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technique. Various types of cleaning methods were investigated and only handcleaning was successful prior to the use of vapor blasting. Hand cleaning involved hand scraping of grooves and wire brushing crowns, and was a long operation. Production cleaning rate was eight pistons per hour at an average cost of $1.25 per piston. The hand operation did not produce desired quality. A vapor blasting machine was developed and one operator is now able to clean a piston in ten minutes. The cost is now about 25¢ per piston and quality of work is much improved.

27–56 "Mechanism of Convective Heat Transfer and its Role in Gas Turbines"—D. G. Wilson; The Chartered Mechanical Engineer, V.2, n.9, Nov. 1955, pp 464-473. Dependence of convective heat transfer on the pattern of fluid flow is discussed. An elementary presentation of the governing principles of fluid dynamics is made and illustrated by examples of the behavior of models. Emphasis is placed on boundary layer. Relative levels of heat transfer from different surfaces are reviewed for different fluids. Heat transfer in a system is governed by nature of the flow which depends on Reynolds number and by nature of fluid expressed as the Prandtl number. Heat exchanger mechanical efficiency is taken to be the ratio of heat transferred to a given amount of work done. Heat exchanger volumetric efficiency is defined as the ratio of heat transferred to the volume of the heat exchanger, which is indicative of weight and cost. Ideal heat exchanger is shown to be of counter flow type having a large cross-section to keep down mean velocities and pressure drops, and small flow passages to reduce total volume. A short length is thus required. The regenerative heat exchanger suits these requirements and can show theoretical mechanical and volumetric efficiencies that permit high thermal ratios, economically obtained, with low volume and power loss. After leakage difficulties are solved the regenerative, rotary, type will likely have a large field of use in low pressure ratio gas turbines. Comparison of heat exchange performance is shown in the table.

Type of Flow	Flow Regime	Reynolds Number	Tube Diam. Inch	Ratio Work Done to Heat Transferred	Ratio Tube Vol. to Heat Transferred
Through tubes	Laminar	1,500	¼	1.00	1.00
Through tubes	Turbulent	4,500	¾	2.17	1.69
Through tubes	Turbulent	20,000	¾	44.9	0.75
Across tubes spaced 2D	Mixed	4,500	¾	134	0.63

Abstract Number *Abstract Title*

Gas turbine blade cooling methods with their advantages are discussed. Boundary layer cooling of blades and combustion chamber liners offers great potentialities. Illustrations and references.

28–56 "PWR Power Plant"—Part I, "The Nuclear Power Generator," J. W. Simpson, Milton Shaw; Part II "Turbine Generator Plant," R. B. Donworth, W. J. Lyman; Westinghouse Engineer, V.15 n.6, Nov. 1955, pp 178-189. *Part I*: The U. S. Atomic Energy Commission is sponsoring the Shippingport Power Plant to further peacetime application of atomic energy. Based on design, construction, operation and maintenance it is expected that future plants can be developed. This plant will serve as a training ground for personnel of other plants. The nuclear reactor will produce a minimum full power rating of 790×10^6 BTU/hr. The reactor plant includes a single reactor heat source with four main coolant loops. A loop incorporates a single stage centrifugal canned-motor pump, heat exchanger section of a steam generator, 16-inch gate type isolation valves, and 18-inch outside diameter interconnecting piping. High purity water serves as coolant and moderator under a pressure of 2000 psi. Flow through the nuclear core is 45000 gpm. Under full power, water temperature to reactor is 508° F. and outlet is 524° F. Considerations in selection of major plant parameters, physical layout of components, reactor vessel, main coolant pumps, steam generators, pressurizing tank, core design, materials, primary auxiliary system, reactor control, plant container and site facilities are discussed. *Part II*: The steam turbine, a single cylinder unit, is rated at 100 megawatts maximum, 1800-rpm. Steam is extracted at three points for feed heating. Saturated steam is supplied at 545 psig for full load. Moisture content at second extraction point is about 11.6 per cent. Thermal efficiency is raised to 29.5 per cent by converting to the regenerative cycle. Station power requirements are estimated as 6000 kw for the nuclear and 3500 kw for the turbine-generation portion. The turbine generator will be an outdoor type.

BOOK REVIEWS & NOTICES

SOUND BARRIER
by Neville Duke & Edward Lanchbery
Published in 1955 by
Philosophical Library, Incorporated
15 East 40th Street
New York, New York
Price $4.50
Reviewed by Commander W. H. Cullin, USN

The Sound Barrier is a book written for laymen that meet its authors' aim, namely, "a clear readable exposition of current aeronautical development." The use of mathematics is negligible and the authors presuppose the readers have a minimum of technical background. The explanations of aeronautical phenomena are excellent and authoritative. The book is highlighted by good use of pictures and schematics to assist the explanations.

The book, one would suppose, would be exclusively a recital of English efforts and successes in relation to the Sound Barrier. However, in the preface to the sixth edition, the authors apologize in these cryptic remarks, "and if, alas, the emphasis lies on American progress, it should be remembered that the U.S. releases news of its developments at an earlier stage than Britain, who will not admit the existence of a new aircraft until it has appeared in the sky."

The book encompasses four parts, (1) Supersonic and High Altitude Flying, (2) Design for Speed (engines, aircraft, and pilot), (3) Design For Use, (4) Things to Come.

In the chapter on supersonic and high altitude flying the authors first cover the fundamentals of the atmosphere and fluid mechanics of high speed flight, and it is done in an excellent manner. However, the English method or choice of words has a debilitating effect upon the explanations. An example is "Below the speed of sound, contraction is the dominating factor; but the higher the speed the greater the factor of expansion until at sonic speed itself there is a stage of fluctuating contraction and expansion that causes a pressure disturbance to travel in rises and falls like the ripples from a stone dropped into a lake; in other words, a sound wave."

This chapter also discusses the effect of local Mach number, or compressibility effects on control of aircraft, in addition to comments on the cause and effect of the phenomena of sonic bangs, and advances a number of current theories to explain them.

The authors further note an interesting report of Raymond Rice, the Chief Engineer of North American Aviation, who estimates that the pressure of a shock wave generated by supersonic flight at 1,750 ft. is about 12 lb/sq. ft., and 50 lb/sq. ft., if the shock wave is set off at 250 ft. The latter is equivalent to the force of a 140 mph hurricane. Experts in England are quoted to consider that if sonic speeds were maintained for a period of 30 sec., the resultant bang might approach the severity of bomb blast. In a lecture to the U. S. Institute of Aeronautical Sciences, Raymond Rice further suggested that as the pressures and directions of shock waves could be predicted, it should be possible to mobilize sonic bangs as a weapon of warfare. His idea was that an aircraft with a Mach Number of about 1.2 or 1.5, and as large a cross-section as possible, could be constructed with the express purpose of generating aimed sonic bangs

against an enemy as an alternative to bombs. (Underscoring is the reviewer's.)

In the engine portion of the chapter, Design for Speed, the authors have used the old chestnut of quoting horsepower potentialities that have no meaning when applied to ram and pulse jet engines. However, the elementary descriptions of the various types of engines such as turbo jet, ram jet, pulse jet, and rockets, combined with the history of the development of these engines, is done in a most clear and interesting manner, and covers American, British, and French efforts.

The authors make some very candid statements, to wit: "Both Armstrong Siddeley and de Havillands are continuing work on the development of the rocket motors, and the Ministry of Supply has its own rocket research station about which practically no information is available. This, it is feared, is not only on account of security, but because Britain lags as far behind the United States in rocket propulsion as the United States was behind Britain in achieving jet-propelled flight in the first instance."

It is considered that an error has been made by the authors in the following statement. "In this case the compressor is sprayed by water which evaporates, cooling the compressor and also the air that it is handling." The normal practice is that the water, or water alcohol mixture, is sprayed directly into the air stream just prior to entering the compressor rather than on the compressor. The benefits claimed by the authors for thrust augmentation by water injection are correct. A very revealing statement made by the authors, especially when the recent commentary on the J40 engine of the U. S. Navy is considered, is the following: "Although the development of a new engine may be initiated by Ministry requirements which are beyond the capacity of existing designs, or from a project planned jointly by aircraft constructor and engine manufacturer, jet engines have been generally kept slightly ahead of aircraft specifications." This is a policy we could well emulate.

In the portion of this chapter, Design for Speed, devoted to aircraft, is an excellent explanation of induced drag, a discussion of boundary layer control, and methods of reducing or forestalling critical Mach Number effects.

Discussions of the aero-isoclinic wing, a supersonic straight wing biplane, reverse thrust, the flexible deck, V.T.O. aircraft and flight power control systems are also included.

A very interesting and extensive discussion is made of the pilot's limitations in relation to new aircraft design (i.e., G forces, prone position for pilots, pressure suits, pressurized cabins). The authors state "There is little difficulty or discomfort, provided the body is properly supported, in sustaining a force of 10 G for periods of from 20 to 40 sec. In direct acceleration, this is the equivalent of from zero to 1,098 mph in 5 sec." The first manned rockets will probably take off with an acceleration of 6 G lasting about a minute, to reach speeds in the neighborhood of 25,000 mph. A further point is made that gives one considerable thought. "If two aircraft with speeds a little faster than those already flown by Bill Bridgeman in the Douglas Skyrocket were to come out of the clouds a mile away travelling head on, neither pilot would have time to see the other machine before the crash occurred." Quite apart from the question of illumination, speed itself sets its own problem as it begins to outpace the nerve impulses of the human system.

The third chapter, "Design For Use," discusses the question of sweep back, new military features, and questions of reliability in the design of commercial aircraft.

The authors take you step by step through the design considerations and the compromises required, in general terms, to produce the trio of British "V" bombers, Vickers Valiant, Glosters Javelin, and the Aero 698, delta wing Vulcan. A similar treatment is made in this portion of the book of commercial jet airliners' design, with cost per passenger mile, extensive testing done, etc. It should be noted, however, the cost per passenger mile and freight cost per ton mile is given in English money abbreviations and therefore subject to further interpretation.

In the final chapter, Things to Come, the authors point out that so far, designers have sought to save weight by dispensing with the fuselage in the experimental flying wing, and have succeeded in dispensing with parts of the tail assembly in delta wing aircraft. They note the only unproductive part of the aircraft, in the aerodynamic sense, that still remains constant, is the landing gear. In view of these comments, a dissertation on the values of the new seaplane configurations is conspicuous by its absence.

The authors bring out a salient point in the fact that Aviation Medical research, in the area of the effects of high speed flight environment on the crew and passengers, should be completed prior to the time the aeronautical engineer first sits down to his drawing board, which is usually 5 to 10 years before the projected airplane is first flown.

The book, "Sound Barrier" is readable and invigorating in its coverage of the material concerning aeronautical development to date and should be of interest to anyone desiring the broad picture of current aviation. The authors' remarks in the final chapter are, I believe, revealing and worthy of mention here again:

"The scientist and the designer have much in common with any artist, and their approach, interpretation, and vision, are just as individual. What one favors, another rejects; and it was through the individual's unwavering faith in sometimes seemingly conflicting convictions that Britain first gained supremacy in jet and high speed flight. Many ways lead to the same end; there is no simple, direct route —that is the crux of the matter, the vital point which must be borne in mind when politicians talk glibly of nationalizing the aircraft industry."

THE THEORY OF AEROELASTICITY

By Y. C. Fung

Published by John Wiley and Sons., Inc., May, 1955

490 pages

Reviewed by Lieut. (jg) I. H. Stockel, U.S.N.R.

Dr. Fung states that his book is an outcome of a course in areoelasticity which has been taught at the California Institute of Technology since 1948. It treats a complex subject at the graduate level; consequently, all who have need for a reference to aeroelasticity will gain by his effort.

Aeroelasticity concerns the mechanical behavior of elastic structures subjected to aerodynamic forces. Prerequisite to its study is an understanding of strength of materials, dynamics of mechanical systems, and elementary and advanced aerodynamics. These are summarized in Chapters 1, 12, 13, 14 and 15.

There are two kinds of aeroelastic problems: the stability problem for which only the conditions of instability are sought; the response problem for which the displacement amplitudes as well as frequencies are desired. These are presented in Chapters 2 through 11.

Dr. Fung's work contains a healthy quantity of physical reasoning. The fundamental principles are emphasized and those assumptions which he finds expedient are honestly admitted and clearly stated. An extensive bibliography of available literature is included at the end of each chapter and frequent and specific reference is made to these listings in the text material.

Chapter 1 reviews strength of materials, elementary aerodynamics and dynamics of mechanical systems. The elementary theories of bending and torsion are reviewed. The reader is reminded to judge the applicability of these elementary theories only by the accuracy with which they describe the influence of load on deformation. The formulation of aeroelastic problems requires that the deformed shape of an elastic structure be determined for its loading and the solution does not include a stress analysis. Shear center is defined, with particular emphasis being given to the number of possible definitions of this term. Elastic axis, flexural center, center of twist and flexual line are defined. The concept of "influence" between load and deformation is developed. The uniqueness of the elastic problem and the symmetry of the "influence" matrices are established.

The generalized aerodynamic force is shown to be a function of angle of attack, Reynolds' Number, Strouhal Number, Mach Number, dynamic pressure and an area. Lift, drag, pitching moment and their associated coefficients are defined. Vortex theory for wings of infinite and finite span is summarized and a wing having an elliptic lift distribution is discussed. The "strip theory" for spanwise lift distribution is described.

The fundamental principles of generalized coordinates and Lagrange's equations are reviewed and the applications of these are demonstrated with five example problems. Normal coordinates are defined and complex representation of harmonic functions is described. Lastly, the torsional oscillations and coupled torsion-flexure oscillations of a cantilever beam are treated.

Chapter 2 introduces the main body of the work with some problems in civil and mechanical engineering. Because the structural shapes are "unstreamlined," these problems are not given a theoretical treatment. Experimental results are reviewed to explain the natures of the aerodynamic forces and several representative examples of aeroelastic oscillation are given.

Chapters 3 and 4 treat steady-state aeroelastic stability problems. Wing divergence is employed to illustrate fundamental concepts and methods of solution. This problem is formulated for an idealized three-dimensional wing. The "strip" assumption is introduced and an "exact" solution is obtained for a rectangular wing. The results of two approximate methods based on an assumed deformed shape (the second of which employs Lagrange's equations) and one method employing successive approximations are compared to the "exact" results. Dr. Fung takes this opportunity to introduce matrices, matrix calculus and the reduction of differential and integral equations into matrix equations with finite differences. An application of the latter is outlined for the divergence of a wing having varying section.

Chapter 4 considers steady-state aeroelastic problems in general. The analysis of wing divergence is extended for steady-state problems to include more accurate aerodynamic theories. Loss of aileron efficiency, reversal of control, aerodynamic lift distribution over a rigid wing, the effect of elastic deformation on lift distribution, swept wings, tail efficiency, static longitudinal stability of an aircraft, and twist-

ing of propeller blades are discussed with varying degrees of analytical development.

The phenomenon of flutter is treated in Chapters 5, 6 and 7. Chapter 5 employes dimensional analyses to give a general discussion. Elastic stiffness and mass balancing are related to flutter prevention and it is shown that flutter occurs when energy is added to the airfoil by the airstream. Experimentation in flutter analysis and similitude are discussed. Chapter 5 concludes with a resumé of the early history of flutter.

Chapter 6 presents two approaches to the problem of flutter of a cantilever wing. To facilitate the introduction of analytical solutions, the first assumes quasi-steady aerodynamic derivatives and employs Galerkin's method. The second, based on linearized two-dimensional thin airfoil theory, is less restrictive: the method of generalized coordinates is used.

Chapter 7 extends the analysis of flutter to the three dimensional wing. Generalized coordinates are employed and the choice of these coordinates and the limitations of this theory are discussed. The subject is closed with some remarks on the control and prevention of flutter.

Chapter 8 introduces the "response" type aeroelastic problem. The response of an airplane to gust loading is employed as a vehicle for explanation. Some mathematical concepts are reviewed and the response to a gust of known character is determined. The statistical aspects of this problem are considered wherein the concepts of probability and distribution functions are included. Lastly, the response of an airplane to a measured gust is calculated.

Chapter 9 continues the considerations of response with discussions of "buffeting" and "stall flutter."

Chapter 10 demonstrates the application of the Laplace transform to the solution of both types of aeroelastic problem, response and stability. These applications are illustrated with examples in "gust" response and flutter. The Laplace transformation and the theorems which govern its use are reviewed briefly.

Chapter 11 concludes the subject of aeroelasticity with a general formulation of aeroelastic problems. The "closed loop" nature of these problems is recognized. They are described with block diagrams in which the functional operation of each block is determined and the net behavior of the total system is sought.

Chapters 12 thru 15 conclude the book with a condensed study of advanced aerodynamics. Much of the aerodynamic theory required by the preceding chapters is included here. The subjects treated are the fundamentals of nonstationary airfoil theory, oscillating airfoils in two-dimensional imcompressible flow, oscillating airfoils in two-dimensional compressible flow, and unsteady motion with an abbreviated description of experiments and experimental results.

CHANGES IN MEMBERSHIP

ADDITIONS TO MEMBERSHIP

The Society is pleased to announce the following additions to its membership since the publication of the November, 1955, JOURNAL.

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USCG Academy, New London, Conn.
Scheetz, Carl G., Midshipman 1/c, USNR
Class 1956, Villanova U.
Mail: 216-A Beech Rd., Garden City, Chester, Pa.
Schleicher, Richard J., Midshipman 1/c, USNR
Class 1956, Villanova U.
Mail: 3512 W. 82nd St., Inglewood 4, Calif.
Weiskittel, James, Cadet, USCG, Class 1956
USCG Academy, New London, Conn.
Wubbold, J. H., Cadet, USCG Class 1956
USCG Academy, New London, Conn.

REJOINED

Eaton, S. W., 302 Barr Bldg., Washington, D.C., Associate Member
Evans, John Harvey, 33 Robinson Rd., Lexington 73, Mass., Civil Member
Marin, Antonio, Capt. Argentine Navy, Chorcas 2521, Buenos Aires, Argentina, Associate Member

RESIGNED

Naval	*Civil*
Adams, Wm. Talmadge II	Bassett, Preston R.
Bower, Edward T.	Brown, Charles Joseph
Chambers, Irving R.	Brunson, Virgil Arthur
Ferguson, Harry Everett	Carroll, Hugh C.
Gregg, William James	Crow, George L.
Ingersoll, Jas. Hinchliff	Curl, Herbert C.
Lee, Carl F.	Gill, Stanley
McEwan, James Guthrie	Hammond, Harry B.
Nichols, S. G.	Hanna, Charles Edmund
Olson, Severt Andrew	Harris, Albert Victor
O'Neill, Marlin I.	Hester, Lewis A.
Reynolds, William A.	Hoyer, Knud
Smith, Paul Bridges	MacCarter, Harold L.
Taylor, William Shipley	Maier, William F.
Wesson, Robert Walter	Miller, Carlyle William
Wheelock, Charles D. R.	Myers, Elmer Francis

Nord, Nils
Reed, R. Stanley
Thompson, Henry H.
Wolcott, Robert W.

Associate

Blum, Lester M.
Davidson, Harvey Dean
Davy, A. C. M.
Favorov, Peter Alexeevich
Kittredge, Francis R.
Newton, John F.
White, H.

DROPPED FROM ROLLS

In accordance with the requirements of the By-Laws, it was necessary on 31 December 1955, to drop from our rolls 104 members who were two years in arrears for dues.

DIED

With genuine regret it is necessary to record the death of the following, reported since the publication of the November, 1955, Journal:

Bowker, Arthur M., Associate Member
Buck, Walter A., Naval Member
Dubertret, Paul, Associate Member
Dyer, W. E. S., Civil Member
Haidet, R. P., Naval Member
Hyland, Bruce A., Associate Member
Hyland, John Joseph, Civil Member
Pluymert, Nicolaas J., Associate Member
Reinders, Jan William, Associate Member
Pannill, Charles Jackson, Associate Member

ASSOCIATION NOTES

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The rules for manuscripts are as simple as we can make them.

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2. Single copy only is required.
3. Mathematical formulae used must be set up, preferably by hand printing, so that there can be no question as to symbols, subscripts and exponents.
4. Any drawing submitted must be black on white. A cloth or paper tracing is acceptable but not required.
5. Photographs may be negatives, but glossy prints are acceptable.
6. *Include on a separate page a short biographical sketch (es) of the author (s).* 50 to 100 *words for* each author is desired.

Manuscripts should be addressed to:

Secretary-Treasurer
American Society of Naval Engineers
1012 14th St., N. W.
Washington 4, D. C.

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NOTICE OF DEATHS

The Society has no satisfactory machinery for obtaining notice of deaths of members. It is particularly desired that we receive such notice upon the death of any past officer, past member of the Council or member of more than twenty years' standing with photographs and short obituaries. It will be appreciated greatly if any member who learns of the death of a member will advise the Secretary-Treasurer.

SOCIETY LAPEL BUTTONS

Shown below is an illustration of the lapel button of the Society. It is believed that it will be conceded that this is a very fine dignified insignia. It is one-half inch in diameter.

The oak leaves and lettering are red on a gold background.

It is available to all members at fifty cents (50c) each.

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